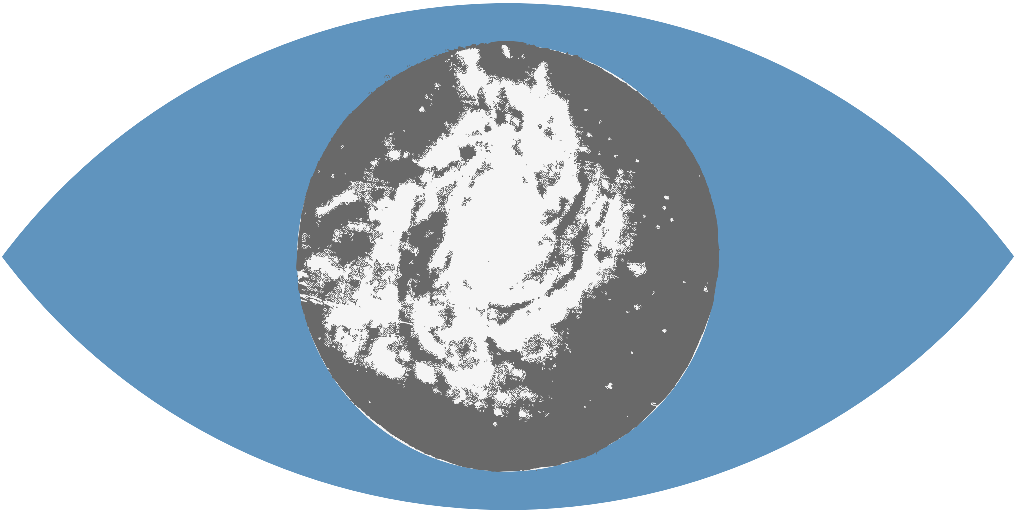
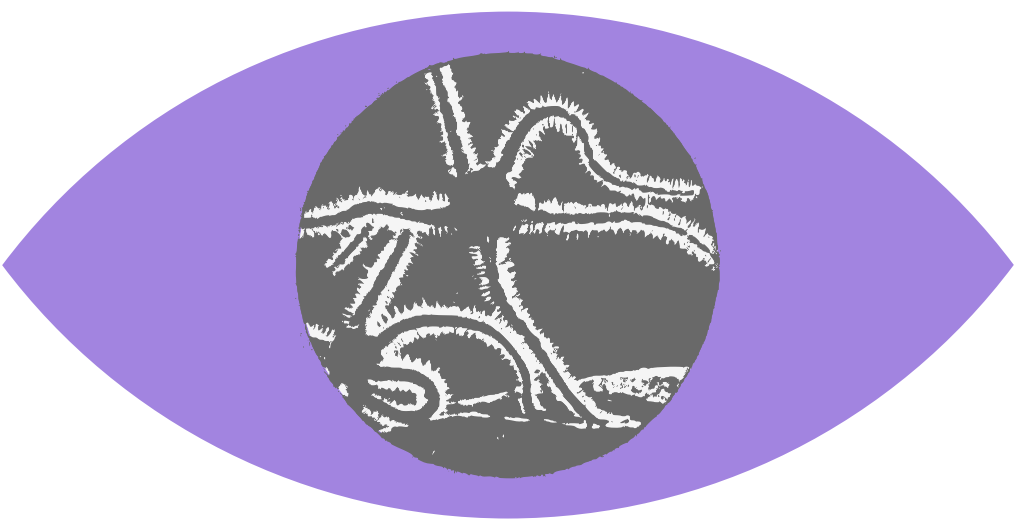


A. STEINHAUS

THE NINE COLOURS OF THE RAINBOW



Have you ever stopped to think how many colours there are in a rainbow? Seven or, perhaps, nine as the title of the book suggests? It appears, there are many more and still the title is correct. Why so?

The book will tell you what is visible and invisible light, how it helps man to acquaint himself with his environment, investigate it, penetrate into the mysteries of matter and space. You wiil also find out how man learned to see in the dark, transmit images over long distances and record processes occurring within millionth fractions of a second. The book contains a wealth of other information on the latest achievements in science and technology.

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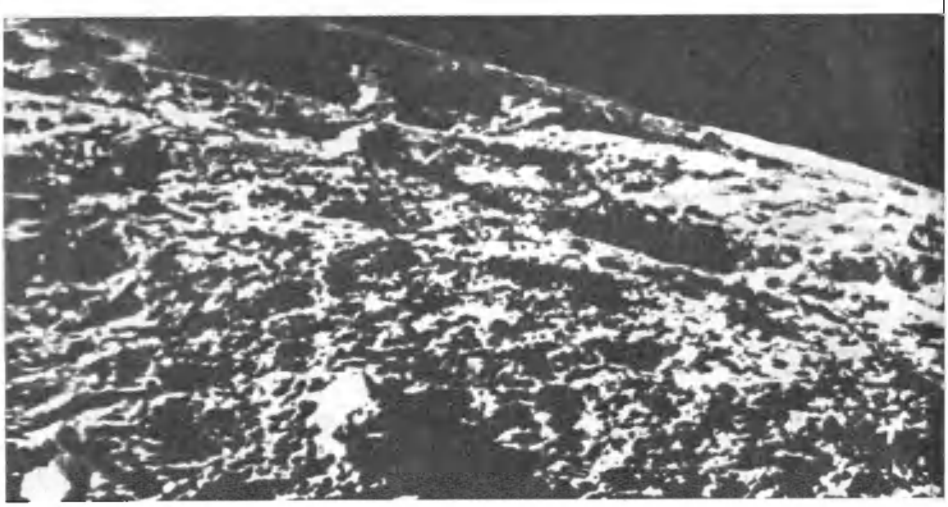
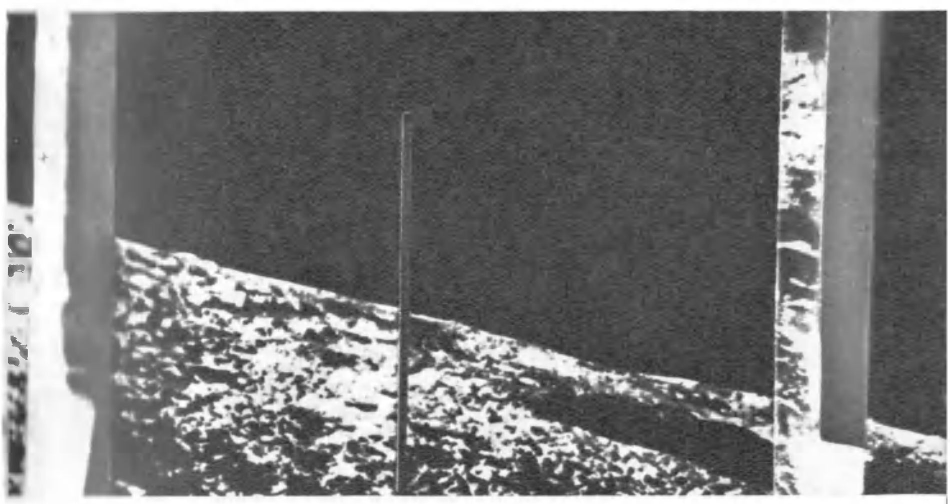


A. STEINHAUS

THE NINE COLOURS of THE RAINBOW

Translated from the Russian by DAVID SOBOLEV



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Under the title is the first photo of the lunar surface sent back to Earth by the TV camera of the Soviet Automatic Space Station Luna-9 in March 1966.

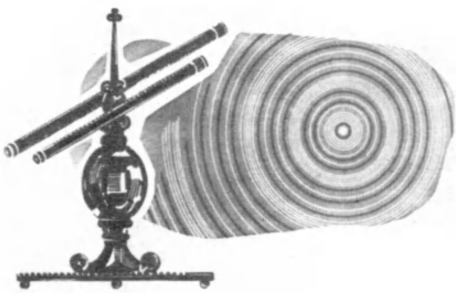
CONTENTS

On colours do most pleasures and delights of our life depend. The beauty of the human face, apparel and other ornaments and hangings, the pleasing appearance of diverse minerals and precious stones, then various kinds of animals, and finally, the brilliance of a beneficial and resplendent sun, all it does create in its magnificence on flowering meadows, in forests and in the seas,—is not all this deserving of our attention?...

But what must be the attitude towards this immeasurable ocean of light of those who direct an inquiring eye into nature's own sanctum and by means of that selfsame light many other natural mysteries do strive to comprehend?

LOMONOSOV.

"Treatise on the Origin of Light, Presenting a New Theory of the Colours...."



LIGHT

Fundamental ideas play the most important role in forming a physical theory. Books on physics are full of complicated mathematical formulae. But thought and ideas, not formulae, are the beginning of every physical theory.

A. EINSTEIN AND L. INFELD.
"The Evolution of Physics."

How many colours are there actually in a rainbow?

Not seven, which is the usual reply, nor nine, as the title of the book asserts, but a great many more, because each colour passes smoothly into the next, forming a multitude of shades. The human eye—an extraordinarily sensitive instrument—can distinguish more than a hundred of them in the spectrum.

But if we mean only the principal colours, and not shades, there are, indeed, seven: red, orange, yellow, green, blue, indigo and violet.

Then the title of the book is wrong?

No, it is not wrong. Because the rainbow has two more bands fringing it above and below. One of them lies beyond the violet, and the other beyond the red boundaries of the

visible part of the rainbow. The eye cannot discern them because it is not sensitive to them, but they exist nevertheless, and can be detected by various means. The band beyond the violet boundary owes its existence to ultraviolet, and that beyond the red boundary, to infrared rays.

The presence of these bands justifies the book's title.

Our eye is insensitive to these rays: it does not see them. In a closed room illuminated by either infrared or ultraviolet rays a person would think he was in complete darkness. However, this is not so: there is light in the room, though of an unusual kind—black light. Black only because it is invisible to us. But infrared rays, for instance, can be felt. If their intensity is high enough the skin will get a sensation of warmth because these rays are heat carriers and are for that reason often called heat rays.

Here one may, and usually does, ask: why bother with ultraviolet and infrared rays at all, what significance can they have and is there any sense discussing them?

It appears, there is. Because they have already been mastered fairly well in science and engineering, and in the future it will be just as impossible to do without them, even in everyday life, as it is now without visible light.

A Piece of Glass

Thousands of years have elapsed since people learned to make glass and with the aid of long tubes to blow various-shaped thin-walled transparent vessels from the molten slightly phosphorescent mass.

The first glass made was not good glass: it was neither pure nor sufficiently transparent; it often contained dark specks, bubbles and other defects. Time passed, and step by step men acquired the skills of glass making. Its quality became better and better, and, which is no less important, it became possible to prepare fairly large pieces with almost no defects.

From such pure and uniform pieces lenses could be made. The first lenses were produced in the early Middle Ages. It is thought that they were invented by the Arabian physicians, who were already at that time quite familiar

with the structure of the human eye. It was the eye, and especially one of its most important parts—the crystalline lens—that suggested grinding the counterpart of the latter from a good piece of glass.

Lenses immediately found application. Naturally, they were used primarily by people with faulty eyesight. Very few could afford to buy these salvatory, but terribly expensive glasses. However, even their happy possessors could not make full use of them, because spectacle rims had not yet been invented.

They were invented only in 1350, evidently in Italy. And that is when spectacles—the first optical instrument—appeared.

Though very few could read and write in those far-off times, and there seemed to be no call to strain one's eyes especially, still, spectacles were in great demand. New trades sprang up, those of lens grinders and opticians.

Of course, very little was known about the laws of optics, and even less about the nature and properties of light. Not that there were no attempts to discover and comprehend them. Scientists have been interested in the laws of optics since times unknown.

Some facts were known to the scientists of ancient Greece. Euclid knew the law of reflection of light, Aristotle studied the refraction of light, and Ptolemy, the famous astronomist of antiquity, even measured the angles of incidence and refraction of light. The Greeks used concave mirrors for kindling.

Optics was studied by Arabian scientists. About nine hundred years ago there appeared a whole scientific treatise on optics by ibn-al-Haytham; for almost four hundred years it was the most complete and best work on the subject.

Many European scientists of the Middle Ages took an interest in the laws of optics. They studied the action of lenses, attempted to explain the phenomenon of the rainbow; they already made experiments in light refraction with the aid of ground glass prisms. This was still far from genuine science in the modern sense.

And yet, it was the piece of glass, made transparent and appropriately shaped by the skilled hands of the

grinder, that was destined to call to life this science, the science of light, or optics as scientists call it.

Strange as it may seem at first glance, but the greatest inventions in optics date back to the time when this science was just coming to life. This refers to the invention of the telescope and the microscope. The first telescopes and microscopes were made in Holland in the beginning of the 1600's. By that time numerous optica shops had appeared in that country, manned by first-rate glass grinders and lapidaries. And legend has it that the telescope was invented in one of these shops. However, it was not an optician, nor a scientist that invented it, but a child who had been allowed to play with the lenses. He accidentally took two lenses and looked at one through the other. What was the amazement and delight of the child and of all the adults around, when on looking through these glasses they found that far-off objects seemed very close, as if only a few steps away!

Indeed, at that time it must have seemed absolutely miraculous, downright wizardry, that distant things could be brought up close literally in the twinkling of an eye, without moving from the spot.

This discovery immediately received universal recognition and widespread practical application—spyglasses made on this principle were a great aid to sea-farers. Scientists became no less interested in the new optical instrument and made just as much use of it. As far back as 1609 the Italian physicist and astronomist Galileo Galilei (1564–1642) made and employed a telescope for observing the heavens.

The first telescopes were very crude instruments. When viewed through them, stars and planets seemed to have rainbow-coloured fringes, and the higher the magnification of the telescope, the more pronounced this colouring became. Craftsmen and scientists strove to discover the nature of these rainbow fringes, many even thought that it had to do with the composition of the glass, but nobody was able to find the right answer until the great English scientist Isaac Newton (1642–1727) took up the question.

Simple Experiments that Explained Very Complex Phenomena and Even the Rainbow

"Light".... The sound of the word usually conjures up the image of white solar light or the warm golden-yellow light of an electric lamp. But other kinds of light may also come to the mind. A driver would possibly recall the blood-red STOP, or calm green GO, traffic light "orbs"; an amateur photographer, the red light by which he often spends hours before his developing and fixing trays; others might picture the bright neon lights of illuminated signs, or fireworks. And they are all right, because light is not necessarily white, but may be colôured as well.

This was known to scientists long before Newton. But before him it never even occurred to anybody that the rays of white light, the light of our Sun, are a mixture of coloured rays—red, orange, yellow, green, blue, indigo, violet, and all the intermediate hues. Moreover, it was known that a prism placed in the path of sunlight produced a bright rainbow-coloured band. But nobody had been able to account for this phenomenon.

Here is what Newton wrote in this connection:

"In the year 1666 (at which time I applied myself to the grinding of optick glasses of other figures than spherical) I procured me a triangular glass prism, to try therewith the celebrated phenomena of colours. And in order thereto, having darkened my chamber, and made a small hole in my window-shuts, to let in a convenient quantity of the Sun's light, I placed my prism at its entrance, that it might thereby be refracted to the opposite wall. It was at first a very pleasing divertisement, to view the vivid and intense colours produced thereby."

Any of us can observe the brightly coloured band cast by a prism on to a white wall or piece of white paper. The colours of the band are so beautiful, intense and pure that one can gaze at them literally for hours with pleasure, ever discerning new resplendant hues. This experiment is easy to perform: all it requires is a prism, say, from a pair of spoiled field glasses. There is even no need to darken the room very much, though the pureness, saturation and number of colours that can be discerned will be considerably lower if you do not.

Newton performed his experiment with sunlight not just for pleasure. His chief aim was to find out why a prism placed in the path of a sunbeam transforms white sunlight into a spectrum—a colour series or band in which all the colours follow one another in an invariable, always recurring sequence.

He had to do an immense amount of work. And if we remember that it was done three hundred years ago with the aid of only a few prisms, lenses and the simplest contrivances, Newton's inventiveness and skill as an experimenter appears positively marvellous.

On the basis of the experiments he performed Newton discovered the hitherto unknown laws of light, and was the first to attempt a scientific explanation of its nature.

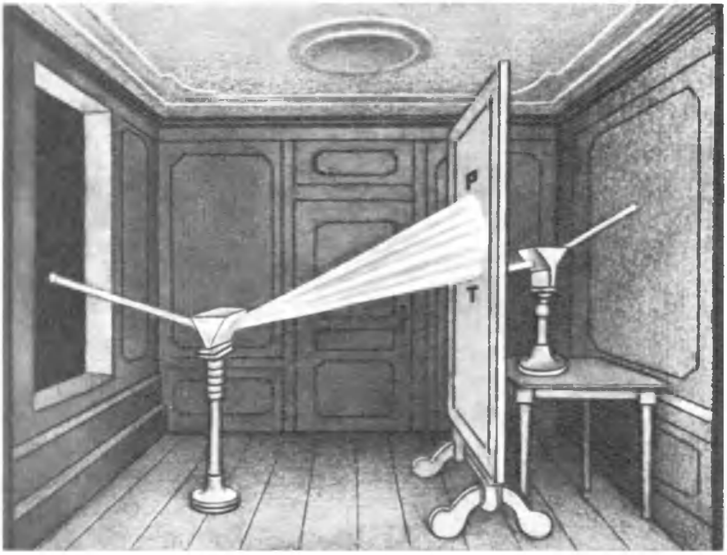
When light rays encounter two media differing in optical properties (for instance, air and glass or air and water), they change their direction on passing from one into the other, i. e., are refracted. The greater the difference in properties of the two media through which the light passes, the greater the refraction. We often observe this phenomenon in everyday practice. Remember what happens when we put a spoon in a glass of water. It seems to have a sharp break exactly at the boundary between the water and the air.

The refraction of light was known before Newton. But nobody knew how rays of different colours are refracted.

In his first experiment (all in all he performed 33 of them, repeating each many times) Newton established that "rays of different colours differ also in degree of refraction". And the third experiment enabled him to draw the following important conclusion: "Sunlight consists of rays of different refrangibility."

Here are some passages from Newton's descriptions of his experiment:

"In a very dark chamber at a round hole about one third part of an inch broad made in the shut of a window I placed a glass prism, whereby the beam of the Sun's light which came in at that hole might be refracted upwards toward the opposite wall of the chamber, and there form a coloured image of the Sun. The axis of the prism (that is, the line passing through the middle of the prism from one



Newton's experiment. On passing through the first prism the solar light is transformed into a spectrum. The opening in the screen placed between the prisms allows the rays of only one hue to pass. For this reason, on passing through the second prism the light no longer forms a diverging beam of rays.

end of it to the other end parallel to the edge of the refracting angle) was in this and the following experiments perpendicular to the incident rays. About this axis I turned the prism slowly, and saw the refracted light on the wall or coloured image of the Sun first to descend and then ascend. Between the descent and ascent when the image seemed stationary, I stopt the prism and fixt it in that posture, that it should be moved no more....

"The prism therefore being placed in this posture, I let the refracted light fall perpendicularly on a sheet of white paper at the opposite wall of the chamber, and observed the figure and dimensions of the solar image formed on the paper by that light....

"...The image of spectrum *PT* was coloured, being red at its least refracted end *T* and violet at its most refracted

end *P*, and yellow, green and blew in the intermediate spaces. . . ."

One of the further theses formulated by Newton on the basis of his experiments states:

"Whiteness and all the grey colours between white and black can be compounded of colours, and the whiteness of the Sun's light is compounded of all the primary colours mixt in a due proportion."

In other words, Newton proved what everybody knows nowadays: that solar light consists of a mixture of different pure colours. No less essential is the fact that uniform light (i. e., "single-coloured" or "monochromatic" light, as opticists call it) on passing through a prism or a lens, is now refracted "regularly". Rays of monochromatic light do not split up on refraction, and therefore an image in monochromatic light is always distinct. As to the rays of white light, they always split up on passing through refracting media. And this is why the images obtained in microscopes, telescopes and other optical instruments were coloured.

In this connection Newton stated plainly:

"The perfection of telescopes is impeded by the different refrangibility of the rays of light."

And only many years later did scientists discover methods of eliminating the colouration of images in optical instruments containing lenses.

Rainbows are also due to the different refrangibility of different-coloured rays.

Long before Newton some scientists had rightly thought that rainbows were due to the refraction of light in falling raindrops. Such, for instance, was the opinion of the famous French scientist René Descartes, but he was unable to account for the appearance of different colours. The first to give the correct explanation was Newton. Nor did he find this very difficult, for he had in his hands the key to the solution—knowledge of the laws of refraction of different-coloured light rays.

On encountering a raindrop, which is very nearly sphere-shaped, the Sun's ray enters it and is refracted. As water is optically denser than air, the ray, on entering the drop, "presses closer" to the perpendicular erected at the point of incidence. It then passes to the opposite side of the drop

and out. But not all of the light comes out this way; some of it is reflected back and emerges at a spot near its point of entrance. Owing to certain reasons most of the light passes out of the drop at an angle of 138° (42°) to the original direction of the Sun's rays. This is the light seen by the observer if he happens to be at the point where these rays arrive.

Then why is the rainbow an arc and not part of a disk?

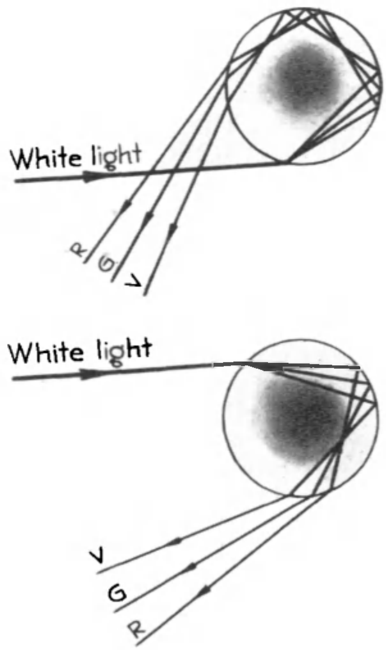
This is due to the fact that the observer's eye catches the light from only those drops, the direction towards which coincides with the return path of the light rays coming out of the drop, i. e., is at an angle of 42° to the direction of the rays coming from the Sun. All the points of space (raindrops, in this case) visible to the observer at the same angle must lie on the circumference of a circle. In other words, the locus of the points visible at a definite angle is a circle. When we observe a rainbow, we see precisely part of a circle, not part of a disk.

Why is a rainbow coloured?

To answer this question we need only recall the laws established by Newton: "Solar light consists of rays of different refrangibility" and "rays of different colours differ also in refrangibility".

Therefore, the angular values 138° and 42° are true for only one of the colours and are different for all the rest. Of course, the difference is not great, because the refrangibilities of variously coloured rays do not differ so very much. But the difference is great enough for the rainbow to become varicoloured.

Often we see two rainbows simultaneously, one above the other, the upper one being much duller and wider, as a rule. This happens when the light is reflected inside the drop twice instead of once before it comes back out into the air. The light emerging after two reflections is weaker, because on the second reflection, as on the first, part of the light is not thrown back, but passes on out of the drop. That is why the upper bow is weaker. The light from it comes to the observer at an angle of 129° (51°) to the Sun's rays. The average angular size of the complete rainbow is 102°, while that of the lower bow is 84°.



The paths of rays through a raindrop. In the lower drop the light is reflected only once and then comes back out. In the upper one, the light is reflected twice before it leaves the drop.

Now, here is a test for your power of observation. Try and recall the order of the colours in the lower and upper bows, starting, say, from the bottom of the lower one.

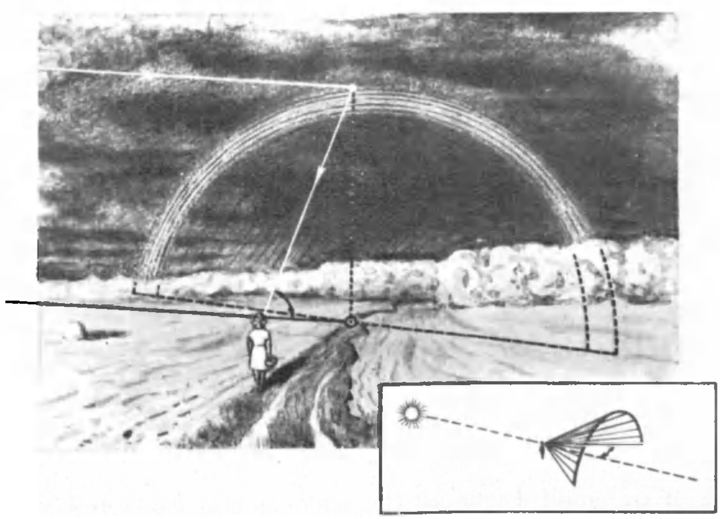
Not many will be able to answer correctly. The order of the colours is as follows: violet, indigo, blue, green, yellow, orange, red. Then comes a band in which the eye cannot discern any colours; sometimes it even seems a little darker than the rest of the sky forming the background of the rainbow. This band is followed by the upper bow; here, the order of colours is reversed—from red to violet.

The violet of the rainbow, especially the upper one, has a pinkish tint and differs from the violet produced by a prism

in a dark room. This is due to the fact that unresolved white solar light is superimposed on it, making the violet hue paler and imparting a reddish tint to it.

They say, the English have an ancient belief: "If you can get to the foot of a rainbow, you will find a pot of gold." But just as it is impossible to get to the horizon, so it is impossible to reach a rainbow. There is another reason why not a single Englishman has ever got rich this way, and that is, because the rainbow has no foot. It is not an arc at all, but a complete circle.

Of course, on the ground, we never see all of it: at best (at sunrise or sunset) its lower part is 42° below the horizon. But if the rain is coming from a cloud 5 or 6 kilometres up, the complete rainbow circle can be seen from the peak of a mountain about 2.5 or 3 kilometres high, or from the cabin of an aeroplane or any other flying machine. Moreover, as the centre of the rainbow is on the continuation of the line joining the Sun and the observer's eye, and the Sun is behind the latter, under favourable conditions,



Relative positions of observer, Sun and rainbow.

he will see the shadow of the mountain or aeroplane, and... his own, as well, exactly in the centre of the rainbow.

They say, some people have had the good fortune to witness such a magnificent sight.

Possibly, some of our readers have wondered why in our latitudes rainbows are seen only in the morning or towards evening, i. e., only in the western or eastern parts of the sky? The answer is simple: the higher the Sun rises, the farther the rainbow descends beyond the horizon or the roofs of the houses, and vice versa, the lower the Sun, the higher and more magnificent the rainbow.

Before passing on to the next section, it will be interesting to mention that the brightness of the colours in the rainbow depends on the size of the raindrops. If they are large, 1 or 2 mm in diameter, the violet and green bands will be very bright, the red will also be quite perceptible, but the blue will be very weak. If the drops are smaller, the red will become less bright. When the drops are 0.2 or 0.3 mm in diameter it disappears entirely, though the rest of the colours remain quite visible. When the drops are still smaller, the rainbow grows wider and paler, and when the drops are very minute, about 0.05 millimetre in size, it becomes white.

However, in speaking of the dependence of the brightness of the rainbow colours on the size of the raindrops we are rather forestalling events: in Newton's time this phenomenon could not yet be explained.

Questions and Answers

Science is not and will never be a closed book. Every important advance brings new questions. Every development reveals, in the long run, new and deeper difficulties.

A. EINSTEIN, L. INFELD.
"The Evolution of Physics."

If we could divide all the sciences into parts and sort them out on shelves, only two shelves would be needed. One would be labelled "How?", the other "Why?".

The first shelf would be very large indeed—it would have to accommodate all the scientific discoveries, all the facts established and investigated by humanity throughout its entire period of existence. The second shelf would not have to be so large—it would hold not so very many volumes filled with hypotheses and theories explaining the facts known to date. While the contents of the first shelf keep being replenished from day to day, and its old stores remain intact, the second shelf is in a state of constant change, continual renewal. In other words, contrary to theories, only rare facts grow old or change, and most of them remain entirely unaltered, eternal, though, of course, they may be refined.

We say: "The Earth is a sphere." This is a fact. True, it is known now that the Earth is slightly flattened at the poles, so that it is not an ideal sphere. But this does not change the significance of the fact; it has just become more accurate. And this fact will remain unchanged as long as the Earth exists. But, having established the fact and verified it by experiment, scientists do not consider their job completed. They seek the answer to the question: "Why is the Earth a sphere?" The answer, no matter what it is, may be considered a hypothesis. Hypotheses can be very different. Often true, more often wrong, and sometimes even foolish. But only few of them survive. Only those are recognized that are borne out by facts and themselves are able to explain not just one phenomenon isolated from others, but a whole multitude of facts, sometimes of a widely different nature at first glance, and, moreover, to foretell the existence of new, hitherto undiscovered phenomena. Such hypotheses pass into the grade of theories. The more facts and phenomena a theory can relate and account for, the more profound and true it is, and the more long-lived.

Theory explains facts, and facts verify theory.

Everything told here so far about light belongs to the category of facts, it is all answers to "How?". The first time we asked "Why?" was when explaining the rainbow. And we found the answer to this question by referring to certain facts, to certain laws of light established by Newton.

Of course, the most important "Why?" in optics concerns not the rainbow, but the very nature of light. ***What***

is light, what its nature, why does it behave thus in some cases and differently in others? For if we could come to know the absolutely exact nature of light, we should in all cases be able to forecast the results of its action. That is why optics, or, more broadly, physics, not only studies and accumulates facts pertaining to light, but strives to comprehend and explain, on the basis of these facts, what light is.

Can scientists find an absolutely exhaustive answer to this question? And will it remain invariable for all time, as it is with the statement that the Earth is a sphere?

The answer is no. It is and always will be impossible to form an absolute theory. There were scientist-philosophers who attempted to create theories of this kind, which dealt with truths in "the last instance", but they were mistaken.

The philosophical works of Marx, Engels and Lenin have revealed the fruitlessness and utter erroneousness of such attempts. Indeed, is it possible to create a perfectly complete theory of any section of science without knowing all the facts and phenomena in that field? *But that is just the point, that we can never come to know everything to perfection. Because the more science progresses, the more knowledge we get, the more new, absolutely unknown fields are laid open before our eyes, and the more new regularities we still have to study.*

But if this is so, does it not mean that people will never be able to know anything for certain and therefore will never be able to build true theories? Of course not.

There are at present many theories that have been verified by life itself, by practice. They explain most known phenomena correctly. But just the same these theories are always being refined and supplemented as our knowledge progresses.

All the above is foregoing exemplified by the history of the theories of light, which we shall now turn to.

The two most important theories, which explained the nature of light in entirely different ways, appeared almost simultaneously.

The author of the first was Newton.

According to his views, light is a substance. Not a continuous, flowing substance, but one that consists of specific particles—corpuscles, as he called them.

Such corpuscles are emitted by all luminous bodies. Impinging on the eye, they cause the sensation of light. Newton accounted for the different colours by asserting that corpuscles are not all the same: the corpuscles of yellow light must differ from those of red light, etc. In short, there must be just as many different kinds of corpuscles as there are different-coloured rays.

Newton's theory, which is often called the emission or corpuscular theory, accounted well for most of the properties of light known at the time.

Thus, the reflection of light from a specular surface can be explained very well by imagining the corpuscle as a tiny elastic sphere which rebounds like a ball after striking a wall, changing its direction in accordance with the law of impact of an elastic body against a plane surface. The emission theory also explained simply and comprehensibly the passage of light through a vacuum. Indeed, nothing should prevent a stream of light particles—corpuscles—from travelling in a vacuum. The same theory explained successfully, though in a more complicated way, the phenomenon of light refraction, and many other facts.

Still, Newton did not consider the theory he had put forth to be final. He pointed out that his opinion was nothing more than a hypothesis, the aim of which was only to make things clear.

"Myself, I," wrote he, "shall accept neither this, nor any other hypothesis.... However, in expounding the hypothesis, to avoid verbosity and for more convenient presentation I shall sometimes speak of it as if I had accepted and believed it."

Possibly, he considered that scientists still knew too little to assert the corpuscular theory to be true. Maybe these words were put down only to fend off excessive arguments with his learned antagonists. There is probably some truth in the latter conjecture, because Newton verbally never admitted the other hypothesis of the wave nature of light put forth by his contemporary, the Dutch physicist Christiaan Huygens (1629–1695).

What Language Does Science Speak?

However, before turning to Huygens' theory, we must digress for a moment to discuss the language of science.

This is a very interesting and exceedingly complicated subject which probably draws the attention of many scientists: philosophers, philologists, physicists, chemists, biologists, and many others. Study of the language of science is extremely important for a number of reasons. But the most important of them is, that owing to the great complexity of science language and as each branch has its own terminology, it not infrequently happens that scientists talking of the same thing, each in his own way, cannot understand one another, and this retards scientific progress.

Until not so long ago this situation could be put up with. But during the last few decades, when numerous discoveries of major importance were made at the borderline of hitherto unrelated fields of knowledge, the problem of terminology, of the language of science, has become one of prime importance. And that is why special committees have been appointed by academies of science and by scientific associations of various countries with the purpose of working out an efficient, and, which is very important, uniform system of terminology covering many branches of knowledge.

New words cannot be coined just in any old way, at one's whim. But what are scientists to do who are always discovering new things? These new things have to be given names. And thus new words have to be thought up. But even in this case it is a very complicated thing to invent a new word, and actually, very few really original words are ever suggested by scientists.

They almost always do otherwise: they try to find words already in existence which are more or less close in meaning to what is needed and use them to denote the new phenomenon. There are several ways of selecting such words, but two are the most widely employed. The first is to use words from dead languages, most frequently ancient Greek or Latin; the other is to take them from one's native tongue. It is hard to say which is the better method. Scientists are equally apt to choose the one as the other. But the

first has one advantage. A dead language is dead because not a single people speaks it and most people (including scientists) do not even know it. For this reason, a word taken from such a language, while being nice and euphonous (having been made up by many, many generations), is not encumbered by its original meaning. It is but a beautiful form which can be filled with a new content only slightly or not at all resembling its original content.

Take, for instance the sonorous word "electron". What does it mean to us? A minute particle of substance contained in the atom. That is how we understand the word.

In Homer's time "electron" had an entirely different meaning—it denoted a transparent yellow stone thrown up at times by the waves on to sea coasts—what we now call amber.*

But Homer is gone, and the people we call the Hellines exist no longer. Left over from those far-off times are some of the world's best works of art and literature, and the language. The first to make use of the latter were the scientists. And they were quite justified in taking advantage of this splendid treasurehouse.

A word borrowed from a dead language can lead no one astray by its former content, and that is just what makes it good for use in science where it acquires a new and absolutely unambiguous meaning. It is convenient also because the word becomes international, being pronounced and understood alike in all languages.

The second method is not always quite so convenient because the word, being a live one, is in common use in a definite language, and its exact equivalent cannot always be found in other languages when translating. The net result is that words come to have different meanings, i. e., become ambiguous, having one meaning in everyday life and an

* The history of the word "electron" in its present-day sense is rather involved. First, the word "electricity" came from the Greek "elektron" (meaning amber), because electric phenomena were first observed by scientists on pieces of amber. But at the time the word "electron" was given its modern meaning (at the end of last century), scientists hardly thought very much about its original meaning. Most likely, "electron" was derived from "electricity", thus completing the cycle: "elektron—electricity—electron".

entirely different one in science. This often causes a lot of confusion.

One must be very careful in interpreting even the simplest and most common words if they are used in science. This should be held in mind when reading any book on science; we shall come up against this question more than once in this book too.

By way of example, consider the simple and well-known word "wave".

A Word from the Dictionary

First of all, let us see what the word "wave" means literally. Or rather, what it meant in those days when science had a less important bearing on the life of humanity than now. This is not difficult. All we have to do is to look up the word in some, say, nineteenth century Oxford dictionary (before 1832):

"Wave I. A movement in the sea or other collection of water, by which a portion of the water rises above the normal level and then subsides...a moving ridge or swell of water between two depressions or 'troughs'...."

But would the compilers of that dictionary—men well versed in English—have understood such a phrase as: "We are broadcasting on frequencies of 16, 19, 31, 41 and 49 metre bands short wave"? They would not, because in this case the word is used in an entirely different sense, introduced by physicists.

It must be admitted, however, that this word was not chosen just casually.

The first kind of wave motion that scientists observed and studied was the motion of waves on a body of water, such as appear and spread when a stone is dropped in or a fish breaks through the surface. Though the waves on the surface of water were the first to be observed by scientists, it was found, as more and more other kinds of waves were studied, that these waves possess a number of distinguishing features. Still, surface waves offer the best starting point in discussing other kinds of waves, and

they are mentioned as such in almost all text books on optics.

Such waves spread in circles. The velocity of their motion is uniform for all the ridges following one another; each subsequent ridge lags behind the one before it exactly the same distance. The distance between two consecutive crests (or hollows) is called the wave-length, though, by analogy with a screw, it would probably be better to call it the wave pitch. Note that the word "length" is also used here in not quite the usual sense; it ordinarily denotes a longitudinal measurement, while here it is a transverse measurement.

Any light object that happens to be in the path of the waves, say, a float or a wood chip, does not move away with the waves, but stays where it is.

This does not mean that the object remains motionless. It rises to the crest, falls into the trough, again rises and again falls. Hence, the wave makes it move. But this motion does not coincide with the direction of propagation of the waves—it is transverse, at right angles to this direction.

Then why does a river current carry off any floating bodies? Does this not contradict what we have just said about waves? By no means. It just suggests the conclusion that waves and current are two entirely different things. On a river we are carried by the current of water, that is, the movement of the entire mass of water in a definite direction. But when a wave passes along the water, each drop, each molecule of water, does not follow it. They stay where they are, just bobbing up and down like the float, oscillating transversely.

However, when we observe waves, we definitely see motion. What is it that moves?

Unfortunately, the answer is not simple and rather unexpected. It is probably best just to memorize it at first, as we memorize a new unusual fact, and become accustomed to it without going into the whys and wherefors for the time being.

Usually, the word motion conjures up in our mind something on the move: an automobile racing down the road, and aeroplane flying through the air, a ship furrowing the

waves, a rolling ball, a man walking, and so on. Our everyday life, all our experience teaches us this meaning of the word. Unless we have specially learned to do so, we cannot understand, and much less picture any form of motion that is not accompanied by the movement of some body.

But the propagation of waves is a kind of motion that differs from what we are used to and understand.

When waves are propagated through water (or any other medium) two kinds of motion must be distinguished. Observing the waves on the surface of water, we see crests and hollows spreading in circles. This is the motion of the waves. They spread from the source of vibrations with equal velocity in all directions. The motion of the waves is quite different from the motion of the water particles associated with it. These particles are also in motion, but they move only up and down. Each particle, *each molecule oscillates with respect to the position it occupied before the waves started, but does not move along with them.* That is why the float stays where it is and only bobs up and down on the waves. Thus, the observed movement of the waves is not a transfer or shift of a body from one point of space to another. *Only the state of the medium moves along.* The movement we observe as continuous widening of the circles on the water *is only the oscillation of its molecules, transmitted from one to another in the direction in which the waves are seen to move.*

A stone thrown into the water acts on the molecules that happened to be in the spot it fell on; it imparts a certain velocity, transfers a certain amount of energy to them. The cohesion between the water molecules is fairly strong. Therefore, the molecules displaced by the falling stone drag their neighbours with them, the latter pass their displacement on to their neighbours, and so the displacement spreads farther and farther.

That is to say, it is precisely the displacement, energy, that moves in the direction of propagation of the waves. The rate of transmission of this energy, or, in other words, the rate of propagation of the waves through the water (or any other medium) depends upon a number of factors, among others, on the properties of the medium through which they are propagated.

Take an ordinary bell, remove its sonorous metallic cup that the hammer beats against, and place it with the hammer touching some water. When we switch on the current, the hammer will begin to vibrate. Its vibrations are transmitted to the water molecules and circles of waves appear on the surface. It has already been mentioned that the velocity of the waves is uniform for all the ridges following one another; each subsequent ridge lags an invariable and equal distance behind its predecessor, this distance being the wave-length.

Suppose at the beginning the bell hammer was vibrating five times a second. Then, by changing the tension of the return spring we considerably increased the frequency of its vibration. Waves continue to appear. But there seem to be more of them, and they come faster. If we could measure the wave-length, we should find it to be shorter in the latter case.

From this experiment we can draw a very important conclusion: *the higher the frequency of vibration, the shorter the wave.*

The mathematical relation between the wave-length, the frequency of vibration and the rate of propagation is very simple:

$$\text{wave-length} = \frac{\text{rate of propagation}}{\text{frequency of vibration of wave source}}$$

or,

$$\lambda = \frac{v}{f}$$

where λ is the wave-length;

f is the frequency of vibration, meaning the number of vibrations per second performed by the wave source, and

v is the rate of propagation of the wave.

All the experiments and reasoning so far pertained only to the waves we observe on the surface of water. Now, let us see what shape the waves will take if we place the source of vibrations deep below the surface.

For this purpose the experiment with the bell should be performed not in a bath tub or in a pond, but out at sea, far from shore, and the bell must be lowered at least

a few dozen metres below the surface. In this case the propagation of the waves will not be hindered by the sides of the tub, or the bottom, or the shore. When the bell is switched on, waves begin to appear in the water. They spread in all directions from the bell like light spreads from the Sun. And, since the velocity is the same in all directions, all the molecules with the same displacement at each moment of time will be at the same distance from the bell. In other words, at each moment of time all these molecules form a spherical surface. The radius of this surface increases continuously, and the rate of its increase equals the velocity of propagation of the waves. But as the vibrations are repeated again and again, the same displacement of molecules will recur at the same spot each time a wave born of the subsequent vibrations comes to it.

The waves we have been talking about up till now, resemble those we are accustomed to. But physicists know other kinds of waves, too. The propagation of sound through the air is also a wave process. Radio communication makes use of radio waves, or electromagnetic waves. These were waves we meant in the phrase on p. 26.

Radio waves have little in common with "moving ridges or swells of water". Moreover, they are capable of spreading through a vacuum. In the latter case they can spread even further than in any other medium.

Not so long ago, this fact seemed incomprehensible even to physicists. They could not understand how a wave could spread through a vacuum. It had always been thought (and confirmed by mathematics) that a wave is a process of transfer from particle to particle and that the latter must infallibly be bonded by some force of interaction.

As the scientists of last century understood them, waves could spread only through some medium. Their existence in a vacuum was tantamount to "nothing" spreading through "nothing." Scientists knew too little to explain such a paradox and, naturally, could not accept this view.

But as they actually observed such waves in nature, they had to account for them in some way.

To do so, physicists were obliged to abandon the concept of absolute vacuum. They were compelled to assume the existence of an omnipresent mysterious substance, a

very fine fluid which they called "ether" and which had a number of unusual properties. In those times, scientists, owing to their lack of knowledge, were in general inclined to account for various physical phenomena by assuming the existence of different elusive substances.

The ether hypothesis was first suggested by Huygens. He needed it to explain the properties of another physical reality—light. Because, unlike Newton, Huygens believed light to have a wave nature.

Free Son of Ether

Possibly, Huygens hit on the idea of the wave nature of light owing to a very important fact, which Newton could not have known of when he started to form his theory of light.

This fact was the enormous, unfathomable velocity of light.

The velocity of sound in air is about 340 metres per second. Some twenty years ago only bullets and cannon shells could move faster. The world speed record established before World War II on an Italian hydroplane was 210 metres per second. The sonic barrier was surpassed by spin-stabilized aeroplanes; their speeds have now risen to well over 2M*, that is, exceed twice the velocity of sound. This is a very great speed.

But in our days this figure has also been left far behind. There are now flying machines which have surpassed higher barriers, viz., the circular and parabolic (or escape) space velocities (equal to about 8,000 and 11,200 metres per second, respectively). These are rockets. But even these values are nothing compared to the velocity of light, which equals 299,780 kilometres per second.

True, during the last few decades scientists have learned to speed up elementary particles of substance, by means of accelerators, to speeds almost equal to this velocity. Particles with such velocities are encountered in nature, too.

But in Huygens' time none of these facts were known,

* M (the Mach number) is the ratio of the flying speed to the velocity of sound in the same medium.

and even musket bullets lagged perceptibly behind the sound of the shot. It is therefore not surprising that Huygens could not imagine any material body; even the minute Newtonian corpuscle, flying at a speed almost a million times greater than that of the propagation of sound waves. It seemed much simpler and more natural to him to conclude that it was the speed of waves rather than of particles.

But if nothing could keep particles from moving through a vacuum, the latter, according to Huygens' views, was an insurmountable obstacle to waves. This is where his ether hypothesis comes in.

Huygens put forth his ideas in a book entitled "A Treatise on Light, in which are Explained the Causes of that which Occurs in Reflexion and Refraction, and Particularly, in the Strange Refraction of Iceland Crystal".

Possibly, the immediate impulse which urged him to write this treatise was the discovery made in 1675 by the Danish astronomer Ole Roemer (1644–1710). Observing eclipses of the satellites of Jupiter, he established that the time of their occurrence was not always the same, but depended on the distance between Jupiter and the Earth. He accounted for this by assuming that light is propagated not instantaneously, but at a certain speed, and on this basis determined the velocity of light for the first time in history.

With respect to this velocity and other facts that astonished him, Huygens wrote: "It is true that we are here supposing a strange velocity that would be a hundred thousand times greater than that of sound. For sound, according to what I have observed, travels about 180 toises* in the time of one second or one beat of the pulse....

"...When we consider the extreme speed with which light spreads on every side and how, when it comes from different regions, even from those directly opposite, the rays traverse one another without hindrance**, one may well understand that when we see a luminous object, it cannot be by any transfer of matter coming to us from this

* A toise is about two metres.

** If the rays consisted of particles, reasons Huygens, the particles of different rays should collide and therefore impede one another.

object in the way in which a shot or an arrow traverses the air; for assuredly that would too greatly impugn these two properties of light."

To Huygens these contradictions were decisive and made him doubt the correctness of the corpuscular theory. However, doubts alone are insufficient to develop a new hypothesis. This requires new concepts and ideas by means of which the nature of light could be explained just as well or better. In Huygens' time scientists had quite a good, though incomplete, idea of how waves are propagated through air and water. And this knowledge enabled Huygens to assert that light was not of a corpuscular but of a wave nature.

What then was the medium, in Huygens' opinion, through which light could be propagated? Water? Yes, light can pass through water. But it is propagated still better through air. Then, air? No, air appeared to be unnecessary for the propagation of light. Huygens placed a sounding body under a glass bell and pumped out the air with the aid of a vacuum pump of the type invented by the British physicist Robert Boyle. The sound ceased to be propagated under the bell, and this showed that it is propagated through air. But no matter how long the air was pumped out, no changes could be observed in the passage of light through the vessel. Huygens could not imagine that light waves should be able to travel in a vacuum—all that was known to scientists about wave processes at that time testified to the fact that waves can exist only in some medium or other. But what is this medium, what its properties? There was no answer to these questions.

"I call it Ethereal matter," wrote Huygens.

But how to detect or isolate it he could not tell. True, he pointed out what ether should be like, in his opinion, in order that light waves could be propagated through it.

"...the particles of the ether, notwithstanding their smallness are in turn composed of other parts ... their springiness consists in the very rapid movement of a subtle matter which penetrates them from every side...."

Thus, according to Huygens' opinion, light is a wave propagated through ether; light and ether are inseparable. But what ether itself is, was not clear even to Huygens.

Pros and Cons

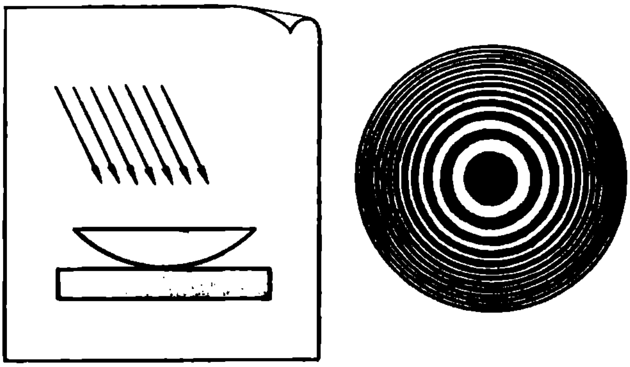
And so, we have become acquainted with two hypotheses which attempted to explain the nature of light. They both came to life almost at the same time, on the basis of the same facts, with the only difference that when Huygens was writing his "Treatise" the velocity of light was already known fairly accurately. But it must not be forgotten that Newton did not change his hypothesis after he learned of Ole Roemer's discovery, believing that it did not contradict this new fact.

Then how can we account for the almost simultaneous appearance of two hypotheses so different in their treatment of the nature of one and the same phenomenon? Only by the fact that both were able to relate and explain logically most of the facts known to science at that time. Most, but not all. It is precisely the existence of weak points in each of the hypotheses that accounts for their almost simultaneous appearance and co-existence. The latter, it is true, was not quite peaceful: the controversy between their adherents lasted many years.

Here are some of the arguments the scientists put forth in this controversy. As the corpuscular theory was the first to appear, we shall begin with the arguments put forth against the wave theory and chiefly against its basic prerequisite—the assertion of the existence of ether.

Neither Newton nor his followers could picture this matter, which filled the Universe, passed through all bodies, remained under a glass bell even after all the air had been pumped out. Besides, they could not agree with the existence in the Universe of an ideally elastic body "approaching perfect hardness" which at the same time is no obstacle to the movement of heavenly bodies, neither stopping them nor even slowing them down.

Denial of ether was the main, though indirect, argument against the wave theory. Indeed, if ether does not exist, then interplanetary space is a vacuum and, therefore, the light from the stars is not transmitted by waves, but is composed of particles, corpuscles, to which a vacuum is no obstacle.



If white light rays are allowed to fall on a lens placed on a piece of well polished glass, rainbow-coloured rings will be observed; these are Newtonian rings. If the light is of only one colour alternating light and dark rings will appear. To make the rings large enough the convexity of the lens must be very small.

The adherents of the wave theory did not leave these arguments unanswered. To substantiate their theory they pointed out a fact established by Newton himself in one of his famous experiments. It was rather a simple experiment. To perform it Newton took two long-focus lenses which he had made for telescopes, one of them a plane-convex lens with a focal length of about 5.2 metres, the other a double-convex one with hardly perceptible curvature, almost flat, having a focal length of nearly 15 metres. With the first lens flat side down on the second, Newton observed an unusual phenomenon. Bright rainbow-coloured rings appeared in the glass. They are now called Newtonian rings. Similar rings, but of one colour only, were observed when the illumination was uniform, monochromatic, say, red.

When white solar light was used the colours in the rings alternated in a definite order: the transparent central spot appearing at the point of contact between the lenses was followed by a blue, then white, yellow and red rings. The next circles, which directly embraced the foregoing ones, were, in the order of their alternation: violet, blue, green, yellow, red. Newton established that these rainbow-like

rings were not conjured up by the lenses, but depended on the distance between the glass surfaces facing each other.

He made similar experiments with other kinds of ground glasses, with prisms, as well. In this case rainbow-coloured bands also appeared which depended on the distance between the contacting surfaces. He carried out no less beautiful and interesting experiments with very thin sheets of mica and with soap bubbles, trying to find the cause of their bright colours, which, as he established, depend on the thickness of the soap bubble film or the thickness of the sheet.

On measuring the ring diameters in the experiment with the lenses, Newton found that these diameters were in a definite periodic relationship to each other and naturally attempted to give it a theoretical grounding. But it must be said that the grounding he gave was not very convincing. Newton felt this himself: possibly, without noticing it he had been inconsistent, patently digressing from his own hypothesis. In his works he even assumed that owing to their attractive or other forces, corpuscles cause oscillations in the medium they act upon. Thus, whether he wished to or not, he at least partly took the standpoint of the wave theory.

Wave shadow of a ship. It becomes perceptible only when the size of the obstacle, for instance, a ship, is much larger than the wave-length; that is why such a shadow was so difficult to detect.

As to the wave theory, it gives an absolutely precise explanation of the appearance of the rings, the bright colouring of soap bubbles, very thin mica plates and even the colouring of certain butterflies, because, according to this hypothesis, the difference in colour is due to the difference in the wave-lengths corresponding to each colour. By the way, only this hypothesis is able to explain why the brightness of the rainbow colours depends on the size of the raindrops.

In objecting to the wave theory, Newton and his followers brought forth one more argument. This was probably the most important, the most essential of them all. To prove that the wave theory is not correct they said that if light were propagated as waves, light rays should go around any obstacle that might be in their way. In other words, light rays would not be rectilinear and no distinct shadows should exist.

Indeed, sound waves and waves on water go around obstacles. A proof of this is that a bell or gun can be heard even though hidden from the observer's view by buildings or hills. With light, however, nothing of the kind was known.

On the contrary, experience showed that shadows thrown off by solar rays, a candle, a lamp or any other light source were always very sharp. This experience was reflected in Newton's hypothesis. One of the most important points of this hypothesis consisted precisely in the statement that light rays are propagated in strictly straight lines and cannot skirt obstacles.

Thus, proof or disproof of the statement that light spreads in straight lines on meeting an obstacle would essentially be the main proof or disproof of Newton's hypothesis.

But in those times the fact that light travels in straight lines seemed obvious to everyone. Only one man doubted it, but he died before either of the hypotheses came into being. This was the Italian physicist Francesco Grimaldi (1618–1663).

Searches, and Again Bells

Books about scientists often tell of unexpected discoveries, of sudden scientific findings. The traditions of such descriptions date back to grey antiquity. Suffice it to mention the legend of how Archimedes discovered his famous law. No less famous is the story of the apple which helped Newton to discover the law of universal gravitation.

However, in telling about the apple, a detail of no small importance is often omitted. Once Newton was asked why such an insignificant fact had made it possible for him to discover one of the most important laws of nature.

"Because," he replied, "I had been thinking of it all the time."

The famous German poet and thinker Johann Wolfgang Goethe who seriously studied light phenomena (he even repeated all Newton's experiments) wrote about one of them: "...the investigator tortured nature, trying to wrest from her acknowledgement of what he was sure of beforehand."

Can you find what you are not looking for? Of course, you can. But only accidentally. And the value of such a find is in most cases no more than that of a stone picked up on a cobblestone road.

People always look for what they want to find. Sometimes they know exactly what they are seeking from previous experience; sometimes they look for what they have never come across before but need very much. In this case they do not know exactly what the thing they are seeking looks like or should look like, but even then they know its properties and, therefore, at least a small part of its distinctive features.

Scientists always have to look for the unknown. Does this mean that when they tackle their difficult but fascinating job they have no idea of the final target? No. They do know a thing or two beforehand. And this "thing or two" suggested by the hypothesis or theory they accept makes it possible finally to find the object of their search or to prove the impossibility of its existence. The latter is often very important and useful.

When we go off picking mushrooms we can picture their shape beforehand; we know that they should be sought only in the woods, and not on a sandy river bank or in a field. This is a theory, if you like. If we were not aware of it, that is, did not know what mushrooms looked like, nor where they grew, we should not bring back a single one of them, even if a basketful of bronze and orange-cap boletuses were placed before us. Because we should not know that these fleshy, pretty, slightly cool objects resembling umbrellas or funny little men in wide-brimmed hats, were mushrooms.

Here is another case. We are off hunting for nuts. We know very well what mushrooms are, but we are not after them. Our eyes are turned upwards into the branches of the nut trees, and we search zealously among the foliage for the delicate straw-coloured nutshells in their green beds. And, of course, we look beneath our feet but rarely, only to keep from stumbling. Are many mushrooms likely to come our way? Well, we might find one or two, and perhaps tramp on a dozen more without ever knowing it.

So it is in science. The most fruitful are purposeful searches, when the aim is clear and the method of search is approximately established.

There are, of course, exceptions when in striving towards one thing one comes across something else no less important on the way. Yet, no sober-minded scientist ever stakes on an accidental discovery. That would be the same as finding an emerald in a heap of cobblestones. But any genuine scientist makes allowance for such an insignificant possibility (and maybe even dreams of it) and he is ready for it. And if, figuratively speaking, he is searching the foliage, he never forgets to have a good look at the trunk and roots. And if he finds anything, as he occasionally does, he is thus rewarded for his incessant attention and love towards the tiniest, most insignificant at first glance, manifestations of nature.

If he just for a moment lessens his vigilance, his attention and interest, he risks not finding even what he is looking for. And this is his greatest punishment.

Thus were punished even the great Newton and Huygens. They knew what they were looking for and where to

look for it, they knew what facts were needed to verify their theories. Moreover, those facts had already been discovered and published by Grimaldi. We cannot tell now why both scientists overlooked them, whether they just failed to notice them or regarded them as conjectures. Who knows? Great scientists—even the greatest—are only human, and may make mistakes.

Evening is falling. Indoors, it is quite dark already; we can hardly discern the letters in the book, the outlines of objects become indistinct, and they merge with the darkness. The click of a switch—and electricity lights up the room. Another click—a second lamp goes on, and it becomes lighter in the room.

But why, for what reason, do two identical lamps give more light than one? Is this not a strange question?

It is—from the point of view of the consumer. But the scientist is quite justified in raising it.

Taking advantage of lighting, we do not go into the reasons why, but just base our actions on experience which has come down to us yet from the caveman who knew that one burning log would light up his lodging less than two and much less than a fire built of a large number of branches.

This cannot satisfy the investigator. He may regard switching on various numbers of lamps as a serious physical experiment. Naturally, he would like to ascertain the quantitative result. He will perform a large amount of work before he comes to the conclusion that the light from several identical sources sums up according to a definite law.

Both the adherents of the corpuscular and of the wave theory will agree with this established fact.

The first will say:

"Yes, and this fact confirms Newton's hypothesis. It agrees with the latter because as the number of light sources grows, so does the quantity of corpuscles emitted per unit surface of the illuminated objects."

The second says:

"Yes, this fact confirms the wave hypothesis. It agrees with the latter because each new light source increases the degree of disturbance of ether, increases the throw (amplitude) of the vibrations of its particles."

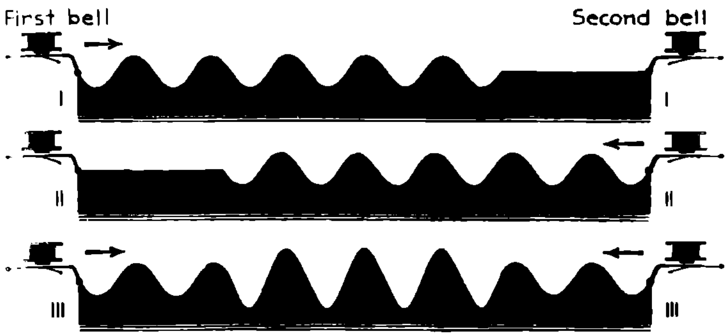
Grimaldi, whom we mentioned above, established another fact. A surprising, strange fact which contradicted everyday experience. He found that under certain conditions light superimposed on light does not enhance the total effect but weakens it. In short, light may give rise to darkness in certain specific cases.

Can such a paradoxical fact be accounted for on the basis of the corpuscular theory? Hardly. Unless we assume that in such cases the corpuscles coming from different sources collide and are annihilated as a result. But this assumption does not tally with facts known to science.

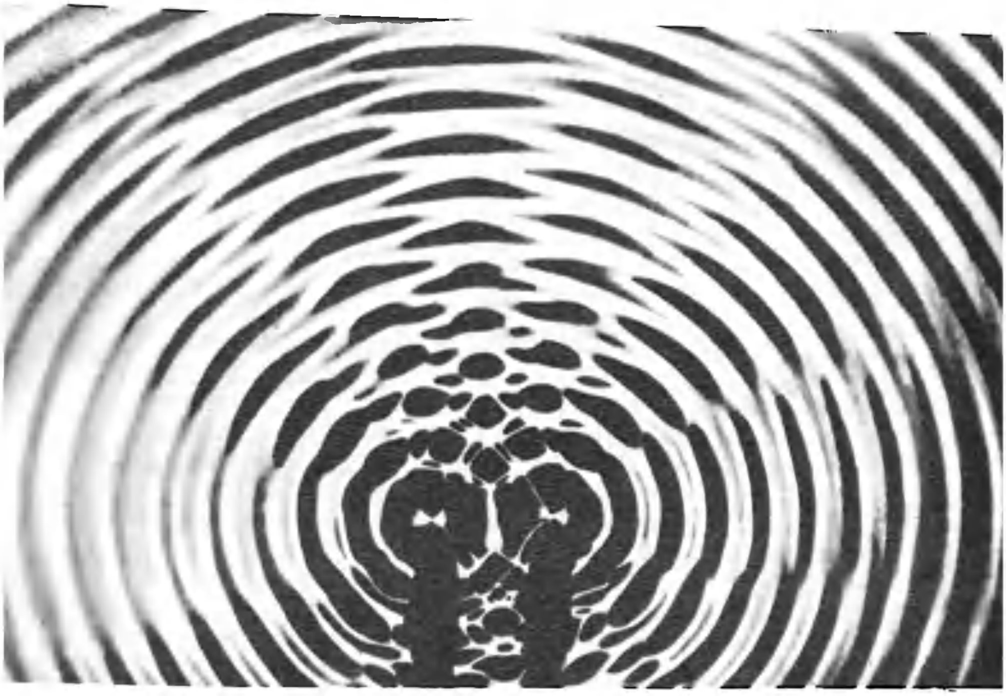
As to the wave theory, it accounts quite easily for Grimaldi's discovery.

Above, we considered the waves on the surface of water spreading from a vibrating bell. The latter was the only source of vibrations. But what would happen if we placed a second identical bell some distance away from the first?

Let us perform such an experiment. But we shall divide it into three parts. At first we shall switch on only the first bell, then only the second bell, and only in the third part of the experiment shall we turn on both bells.



Experiment with bells.
I —only first bell ringing: waves have not yet reached second bell; II —only second bell ringing: waves have not yet reached first bell; III—both bells ringing: waves from both bells meet half-way and begin to interact. Throw of vibrations increases.



This is a photograph of the interaction of waves from two vibration sources.

To be able to observe the results of the experiment better, we shall put a float on the water, placing it somewhere on the line connecting the bells. Before beginning, we must recall once more that waves in water are nothing but the displacement of molecules up and down at right angles to the motion of the wave.

We switch on the first bell. After the first ridge reaches the float and raises it, the latter will continue to rise and fall on the waves as long as they exist. The frequency of oscillation of the float will be exactly equal to the frequency of beats of the bell.

Now we switch on the second bell (with the first turned off). The same occurs as before with the only difference that now the waves arrive at the float from the opposite side.

The third part of the experiment requires careful preparation. Both the bells must be adjusted so that their frequency of vibration is exactly the same. The electromagnet

coils should be connected to a common switch to ensure that they are turned on simultaneously.

We switch on both bells. Waves begin to run in circles over the water from each of them. But there, they meet, first they touch each other, and then intersect. And after this has happened the wave pattern changes. We no longer see the former circles: the waves form a new complex pattern on the water. The float also behaves otherwise. If in the first two stages of the experiment the behaviour of the float was the same at any point along the line connecting the bells, it now depends on the points of this line at which it is situated. At some of them it will oscillate at the same frequency as the bells, but the throw of its oscillations will be greater; but in others the float behaves as if there were no waves at all.

Why is this?

It is because the oscillations—the displacement of the water molecules at each point—now depends on the action of two systems of waves, and not one. Thus, at a given point one wave may tend to make the molecules move downwards at a given moment, while the other tends to make them rise. The net result is that the molecule remains stationary, as does the float. At other points, depending on their distance from the bells, the opposite may happen: both waves tend to make the molecule move in the same direction. And then it will be displaced more than under the action of only one wave—the float will oscillate with a greater throw.

And so, from our experiment we see that waves can interact with one another. Hence, proceeding from the wave theory, we can easily account for the phenomenon first noted by Grimaldi; and the appearance of the famous Newtonian rings can be explained in the same way. In the language of physics this interaction of waves is called "interference".

Light and Shade

And yet, the phenomenon of interference was not the only proof by means of which the truth of the wave theory of light was established. The decisive fact was the phenom-

enon of diffraction, also discovered by Grimaldi. Diffraction is the phenomenon of non-rectilinear propagation of light near obstacles, of light "trespassing" into the region of shade.

But this fact, mentioned in Grimaldi's book, had either failed to draw the attention of Newton and Huygens or was unknown to them. After the death of Newton and Huygens the controversy as to the nature of light stopped as if of its own accord. For many years (until the beginning of the XIX century) the corpuscular theory reigned triumphant in science, though Grimaldi's treatise, forgotten by all, grew dusty and mildewy on the library shelves of several academies and universities. Newton's deserved authority as one of the greatest physicists was the decisive argument used by his less prominent followers to prove the truth of the corpuscular theory.

But it was not merely an accident that the facts confirming the wave nature of light were forgotten. They were, indeed, established by Grimaldi, but only very approximately, in the most general and not very definite form, before Newton's and Huygens' investigations.

No less important was the fact that in carrying out experiments in interference and diffraction of light the experimental physicist has to make very accurate measurements of distances and sizes. In some cases these measurements must be accurate to one or even a fraction of the length of a light wave. And this value is very small indeed.

In Newton and Huygens' time the technique of accurate measurement was very imperfect, fine mechanics was just coming into being. But this was not all. The scientists of those times did not know, and hardly supposed that the lengths of light waves were exceedingly small. The more so, that they already knew how immense the velocity of light was. And the higher the rate of propagation of a wave, the longer it is. Possibly, owing to this fact they might have thought that light waves were very long, if they existed at all.

Subsequently, when scientists succeeded in carrying out the measurements, the results turned out to be extraordinary. It was found that the shortest waves that could yet be perceived by the human eye (violet light waves)

were 0.00038 millimetre or 380 millimicrons long, and the longest (red light waves) 0.00078 millimetre or 780 millimicrons.

Taking advantage of the formula relating the wavelength to the frequency of vibration and the rate of propagation, we get figures that would have frightened Huygens' adherents. The frequency of violet light is about 800×10^{12} vibrations per second, and that of red light, 387×10^{12}!

The wave theory owes its resurrection to many physicists, primarily to the French scientist Augustin Jean Fresnel (1788–1827) and the English scientist Thomas Young (1773–1829) who carried out very important research into the phenomena of interference and diffraction of light and explained them. It was their works that converted Huygens' hypothesis from a daring but experimentally unverified scientific conjecture into a rigorous theory supported by exact facts. In its turn this theory made it possible to reveal and explain many new scientific facts.

What is diffraction and how does it manifest itself?

We can reproduce the phenomenon of light diffraction in a very primitive and purely qualitative manner. In this respect we shall be much closer to Grimaldi than to Fresnel and Young: like the former, we have no precise scientific instruments at our disposal. However, we shall not need them in this case. It is all very simple.

In the evening when it grows dark and the street lights are switched on, select one of the distant, but sufficiently bright, lamps. It resembles a bright golden-yellow point. Now look at it through the slit between your fingers when held together not very tightly, or better, through a thin slit made with a razor blade in a piece of thick paper. When we look at the lamp through the slit we no longer see a bright point, but a light band with dark transverse lines on it, and this band will be at right angles to the slit.*

The only way of accounting for this fact is by admitting that on meeting a small obstacle (say, the edge of the slit) light skirts it and spreads into the region where, according

* Diffraction is conveniently observed through a very fine metal screen. Such screens (of bronze or brass) are often used in different kinds of filters.

to Newton's followers, there should be only unbroken shade. In other words, it must be admitted that on encountering small obstacles (commensurable with the wave-length of light), light ceases to travel in straight lines and is capable of going around the obstacles.

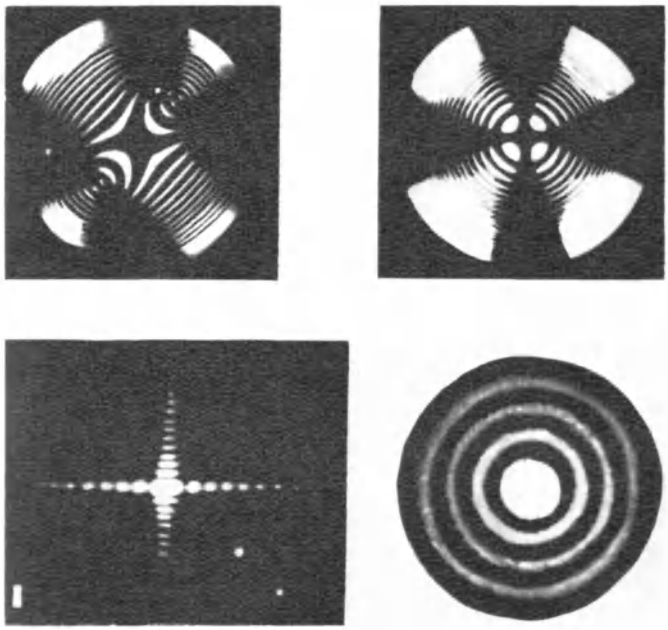
By the way, the waves on the surface of water do not always go around obstacles either. If their length is much smaller than the obstacle, a wave shadow can be observed beyond the obstacle. In this respect the difference between light waves and the waves on water lies only in their lengths and, therefore, in the size of the obstacle.

Light diffraction results in other interesting and at first glance unexpected phenomena. If a ball is placed in the path of light, its shadow on a sufficiently distant screen will not be a uniform dark circle. It will become a number of concentric alternating dark and light bands. A similar pattern will result if a disk or a round small opening in an opaque screen is placed in the path of the light.

It took quite a struggle to win recognition for the wave theory. One of its interesting episodes took place at a meeting of the Paris Academy of Sciences, where Fresnel read his "memoir" describing experiments and investigations which confirmed the validity of the wave theory of light. One of those who disagreed with Fresnel was the famous mathematician Poisson. He had made a careful study of Fresnel's work and intended to slay his antagonist with his own weapon. Using Fresnel's method, he carried out calculations from which it followed that there should be a light spot in the centre of the ball's shadow. At the time these calculations were made this fact was not yet known. And this, in the mathematician's opinion, gave him the right to consider the wave theory wrong.

But his triumph did not last long. Arago, an adherent of the wave theory, performed a special experiment and reproduced what theory and calculations had forecast. And Poisson was thus proved to be right... in that there actually was a light spot in the centre of the ball's shadow. Evidently, there is a measure of truth in the joke some mathematicians like to repeat that "formulas are wiser than we".

Very important theoretically, interference and diffraction have long since been put effectively to practical use.



The two upper photographs show ***light interference.*** *The two lower ones show* ***light diffraction by a*** *rectangular* ***and a circular*** *opening, respectively.*

Many important instruments have been designed on the basis of these phenomena by means of which very precise measurements and investigations can be performed. For example, diffraction made it possible to create one of the types of spectroscopes—instruments employed to investigate the spectral composition of the light emitted by various sources, from a firefly to the most distant stars. The spectroscope makes it possible to determine the chemical composition of a great variety of substances. Spectroscopes of this kind require special diffraction gratings, some of the modern ones containing as many as 25 thousand slits per centimetre.

Light and Electricity

Almost one and a half centuries passed before Huygens' daring scientific hypothesis was verified and confirmed by experiment. It became a recognized theory. And soon Newton had no adherents or followers left among the scientists, for, no matter what experiments were performed to verify or even to disprove this theory, they all led to the same conclusion: they invariably confirmed the wave nature of light.

Well, and what about ether—that strange elusive form of matter with its wonderful, even unbelievable properties? Scientists were obliged to admit its existence too, though ether had not become any more comprehensible as a medium or as a substance. Moreover, after certain investigations connected with what is known as the polarization of light, the properties which scientists were obliged to attribute to ether turned out to be still more incredible.

But what could be done about it? Without ether nobody could explain how light travels through space. And this fact remained the only proof of the existence of ether. The only one because not even the cleverest and subtlest experiments could give direct evidence of the existence of ether—it was not to be detected. Scientists were compelled to admit the existence of this mysterious ether because without it they could not account for the obvious fact that light travels. They thought light to be a vibratory motion of ether. But they did not know the primary cause, the source of these vibrations. Rather, they knew very well that any strongly heated body emits light, but why and how was a mystery to them.

The relation between light phenomena and other physical processes also remained unknown. Thus, the physics of light and the physics of electricity seemed to be divided by a bottomless chasm. There was not the least sign that at any time in the future a point of contact or, still less, that a close relation would be revealed between them. The first to bridge the gap between light and magnetism was the English physicist Michael Faraday (1791–1867) to whom electricity owes as much as mechanics and mathematics owe to Newton. In 1846 Faraday noticed in one of his

experiments that the direction of polarization of light changes under the action of a magnetic field. "I succeeded in magnetizing and electrifying a light ray," he recorded in his journal. Actually the phenomenon was slightly different from what the scientist thought it was, but this did not make the experiment less valuable. Its value to science is difficult to overrate because it established for the first time that there was a relation between light and magnetism and, hence, between light and electricity.

In 1862 Faraday performed a much finer experiment, which, if it had succeeded, would have proved still more obviously the relation between light and electricity. But the experiment failed. And it failed only because the scientist was inadequately "armed": his spectroscope was not sensitive enough, and his magnet too weak. Faraday's experiment was performed successfully only after his death, by the Dutch physicist Pieter Zeeman in 1896. It brought scientists such important data that they served as the basis for the first attempt to build a theoretical model of the atom.

It was the prominent Scottish physicist James Clerk Maxwell (1831–1879) who was destined to disclose the intimate relation between light and electricity. His theoretical studies, which still draw the admiration of specialists by their force and depth, revealed the propagation of electromagnetic vibrations also to be a wave process.

Maxwell made another exceedingly important discovery, that the rate of propagation of electromagnetic waves equals the velocity of light. Developing his theory further, Maxwell in 1873 came to the inevitable conclusion that by nature light also falls into the category of electromagnetic vibrations.

Many people think that a genuine scientist is a man possessing certain specific qualities and traits of character. This idea is not correct, but each scientist has his own style of work. This is especially evident from the examples of Newton, Faraday and Maxwell. Newton was equally as great a mathematician as a physicist. He was a brilliant experimenter, and all his theories which he presented in mathematical form when necessary were based more or less on his own experimental work.

Faraday was different. He hardly ever resorted to mathematics. His ideas of the processes he studied were almost palpably vivid: he could literally feel what he was investigating. And that is why his experiments are always so graphic and comprehensible. This quality of Faraday's was pointed out by his follower, Maxwell.

But Maxwell himself, contrary to his predecessor, never resorted to experiment personally. He was a pure theoretician and a prominent mathematician. Many even share the opinion that his role in the physics of electricity lay chiefly in the fact that he systematized and expressed in the language of mathematics the aggregate of knowledge and ideas established and suggested mainly by Faraday. Maxwell himself was of approximately the same opinion; he wrote:

"I specially undertook this work in the hope that I would be able to give his (Faraday's—*A. S.*) ideas and methods mathematical expression."

This is true to some extent, but actually Maxwell went much further. On the basis of his equations he was able to derive a most intimate relationship between light and electromagnetic vibrations. The importance of this discovery is difficult to overrate. Maxwell was a pure theoretician and was probably absolutely convinced of the truth of his theory. Not so many other scientists. For many years even prominent physicists could not understand it and considered it wrong. To win it recognition special experiments had to be performed which would prove or disprove in practice the truth of his new theoretical constructions. But Maxwell could not do them himself, he could only wait for others to do them.

For a long time nobody knew how to perform the necessary experiments. And only fifteen years after the discovery was made "on paper", and ten years after the death of its author, in 1888, was it reproduced in actual experiment. This was accomplished by the German physicist Heinrich Rudolph Hertz (1857–1894). It was his experiments that made it possible for the Russian scientist Alexander Popov (1859–1905) to invent the radio.

In his experiments Hertz obtained electromagnetic vibrations with a wave-length of from 60 centimetres to

several metres. The Russian scientist Pyotr Lebedev (1866–1912), on reproducing Hertz's experiments, obtained much shorter waves (down to 6 millimetres long), and in 1926 A. Levitskaya designed a special system of oscillators by means of which vibrations could be generated with wave-lengths ranging from 30 to 915 microns.

After Hertz's experiments no one doubted the truth of Maxwell's theory any longer. Some physicists even thought the nature of light had thus been revealed in full, that all the basic facts about light were now known. Perhaps they were still a bit worried about the lack of harmony in the ether theory, but they hoped that in the future this shortcoming would be removed. These scientists thought that the nature of ether would finally become clear. But though they understood tne difficulties brought up by the ether theory they harboured no doubts as to its existence.

Two Discoveries

Back in 1836 Faraday made a detailed study of the passage of current through solutions of electrolytes and formulated the two laws of electrolysis. Besides, he established that in this case the current is carried by ions: positively charged cations and negatively charged anions. As we know, electric current can pass not only through electrolytes, but through metals as well, and all types of electrical discharges in gases are due to the passage of current. However, in those times the mechanism of electrical conductivity of metals and gases was entirely unknown. Nor were the carriers of the current known. Faraday expected that careful study of gas discharges would yield very valuable data for science. But he himself did not go into this question, devoting most of his attention to the study of electromagnetic phenomena.

The passage of current through rarefied gases was investigated by many scientists. This phenomenon is known in detail now, and there would be no point in mentioning it here, if it were not for the fact that its first investigators had made a very important observation in passing. In its turn, this observation led to a discovery which, one

may say without exaggerating, determines the life and destiny of mankind today. This is the discovery of the electron.

Gas discharges were first studied by Julius Plücker and Johann Wilhelm Hittorf in Germany and William Crookes in England. All three of them noted the same phenomenon, but Crookes was able to study it in more detail. The discharges were studied with the aid of Geissler tubes—elongated glass bulbs with sealed off ends, so named after the skilled glass blower Heinrich Geissler. Two metal plates inside the tube served as electrodes—an anode and a cathode. The former was connected to the positive and the latter to the negative pole of a source of electricity. Besides, the tube had a glass branch through which the gas filling it could be evacuated.

When the gas was under ordinary pressures no electrical discharge was observed. The discharge appeared only after evacuation had begun and the pressure had fallen. The gas would begin to glow, and the luminosity would change continuously with decreasing pressure. First the glow would be concentrated around the anode, then the luminous column would grow longer and the tube would become filled with light: violet, if the gas inside was air, lilac-coloured, if it was nitrogen and pinkish if it was hydrogen. Further evacuation caused the luminosity to grow gradually dimmer and finally to disappear altogether.

But the inquisitiveness peculiar to scientists made them continue pumping even after the luminosity had disappeared, and this brought them up against a new incomprehensible phenomenon. The luminosity reappeared, but this time it was not the insignificant residue of gas that produced the light. The yellowish-green glow came from the glass surface of the tube, not from all of it, but from the part opposite the cathode.

In studying this phenomenon, Crookes came to the conclusion that it was caused by certain rays emitted by the cathode. And that is what he called them—"cathode rays". He established that these rays travel at a tremendous speed in a straight line, but can be deflected by a magnetic field. Another manifestation of their action was a perceptible rise in temperature at the place of their incidence. A light

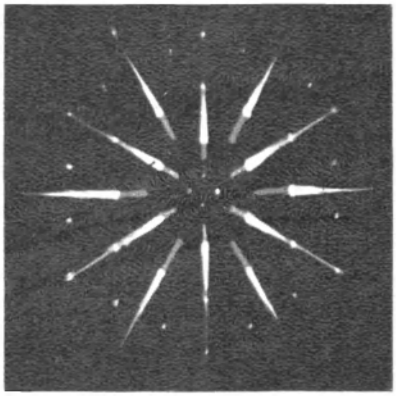
metal vane wheel placed inside the tube in the path of the mysterious rays began to rotate like the arms of a windmill on a windy day. In 1897 Crookes reported his experiments and observations to his fellow-scientists.

Though Crookes had named the phenomenon he had been studying cathode rays, he was certain that actually he had to do with a stream of particles as yet unknown to science. His conviction was shared by the physicist George Johnstone Stoney, who was the first to call these particles electrons. Soon Crookes' assumptions were found to be true—the electron actually turned out to be a particle carrying the smallest possible electric charge and having a very small mass. Nevertheless, both were successfully measured. Though these figures are too small to be grasped by the human mind, they are worth quoting: the charge is negative and equals 0.000 000 000 000 000 000 160 100 coulomb, while the mass is a figure with a still larger number of naughts: 0.000 000 000 000 000 000 000 000 000 910 600 gramme, that is, about 1,850 times smaller than that of a hydrogen atom. The discovery of the electron proved that the atom is not by any means an indivisible particle of matter, but consists of still smaller particles. The practical consequence of the discovery of the electron was the birth of atomic physics and electronics.

In November 1895 a no longer young professor of physics at Würzburg, Wilhelm Konrad Roentgen (1845–1923) joined in the research into gas discharges. In starting his new studies, Roentgen never dreamed that literally during the first week of his work with the Geissler tube he would discover wonderful new rays—"x-rays", as he called them, or "roentgen rays", as they are often called now.

The properties of these rays turned out to be extraordinary. They readily penetrated most substances which are opaque to ordinary light; they can be weakened only by metals, especially lead. Roentgen said that a solid is to x rays what a room full of tobacco smoke is to ordinary light. These rays make an electroscope lose its charge, darken a photographic emulsion and cause certain compounds to glow or, scientifically speaking, fluoresce. Such compounds are used to coat screens in x-ray apparatus.

And still, despite their unusual properties, roentgen



This beautiful symmetrical ornament was "drawn" by x-rays diffracted by an ice crystal.

rays are of the same nature as visible light. They carry no charge, are deflected neither in an electrostatic nor in a magnetic field, and all their differences from light are due to the very short length of their waves, which ranges from 0.049 to 0.000 01 micron. These waves are so short that their diffraction cannot be observed even with the best diffraction gratings having up to 25 thousand lines per centimetre.

Roentgen rays are diffracted only by crystal structures. In our days this property is utilized for studying the structure and inner properties of a great variety of substances.

Spectrum of Electromagnetic Vibrations

Now we know quite a lot about light and can stop and review our knowledge to make it clear what place light occupies in the overall spectrum of electromagnetic vibrations. We shall start with the longest waves (the slowest vibrations) and then pass down the spectrum towards shorter and shorter waves.

But first of all we recommend that the reader should memorize the name and meaning of a very frequently used unit. It is called the *hertz*, after the physicist Heinrich Hertz.

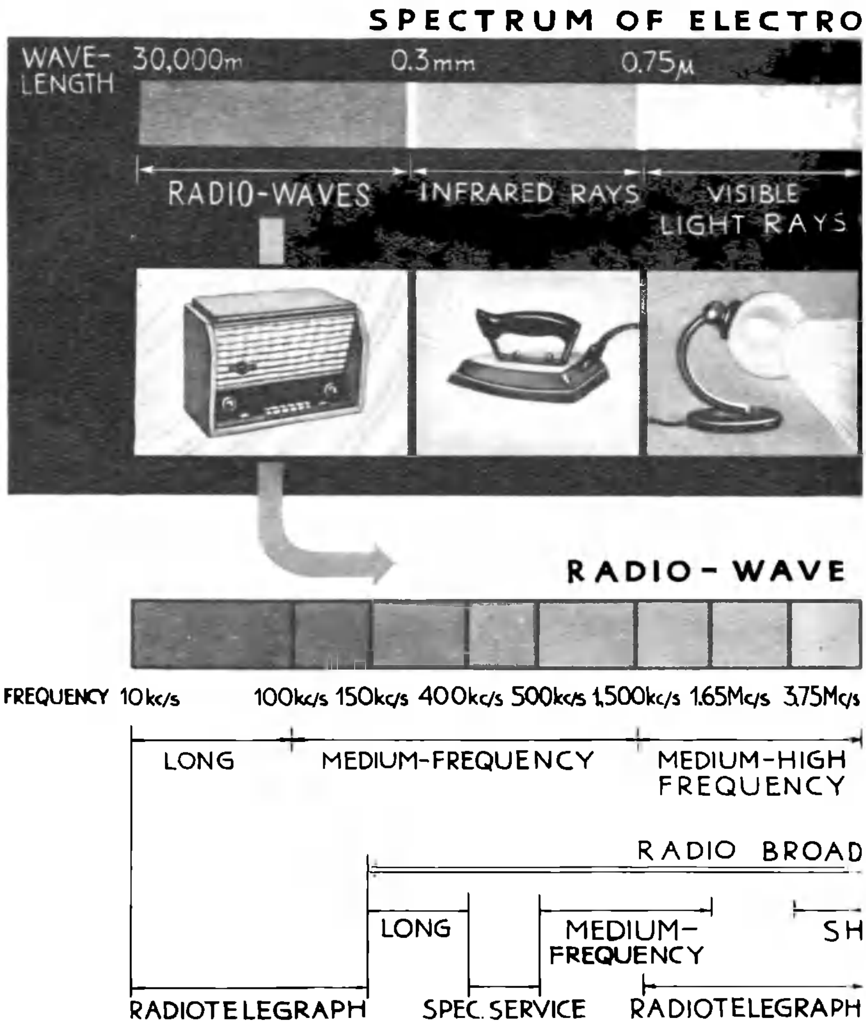
It is used to measure vibration frequencies; one hertz means a frequency of one vibration per second, or one cycle per second. 1,000 hertz or 1 kilohertz is the same as 1,000 cycles or 1 kilocycle per second. 1,000,000 hertz = 1,000 kilohertz = 1 megahertz = 1,000,000 cycles per second or 1,000 kilocycles per second or 1 megacycle per second.

One of the longest-wave vibrations is the alternating current produced by electric power stations. In the U.S.S.R. and other European countries its frequency is 50 hertz.* The wave-length of industrial alternating current is 6,000 kilometres. At present the longest electric transmission lines have not yet exceeded 2,000 kilometres, and therefore the entire line can accommodate only 1/3 wave.

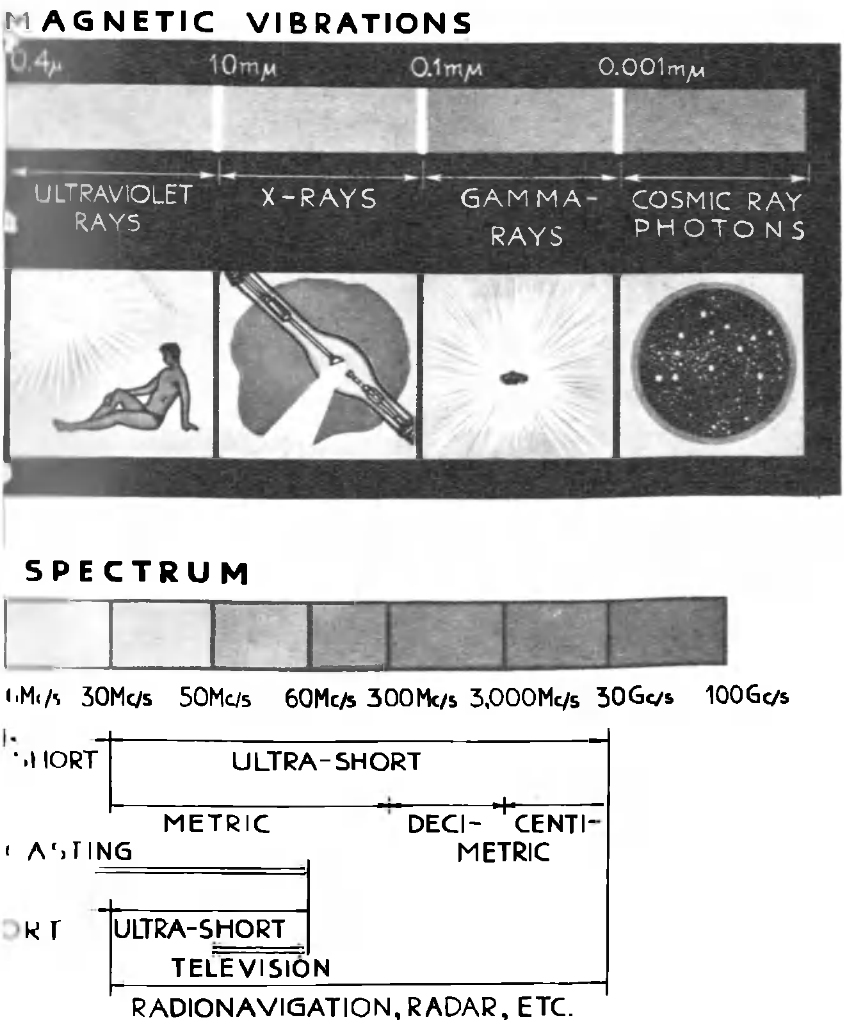
Higher frequencies are used in telephone and wire broadcasting signals. They cover rather a wide band, from 20 to 60 hertz to 20×10^3 hertz. This band is often called the band of audio frequencies, because our ear perceives sonic vibrations (but not the electromagnetic vibrations we are talking about!) of the same frequencies. The wave-lengths in this band range from 15 thousand to 150 kilometres. For comparison it may be stated that sonic vibrations of the same frequencies when travelling through air at atmospheric pressure cause waves (sonic, not electromagnetic!) from 17 metres to 1.7 centimetres long. This is natural—the rate of propagation of electromagnetic vibrations is approximately 300 thousand kilometres per second, while that of sonic waves is only 340 metres per second. The sonic frequency band is followed by the band of infralow radio frequencies. It was called that by analogy with light rays having longer wave-lengths than visible rays. This band ranges from frequencies of 20×10^3 to 100×10^3 hertz. The wave-lengths lie between 150 and 3 kilometres. These frequencies are widely employed in engineering at industrial plants for heating and melting metals by high frequency currents, and also for certain types of long-range radio navigation and radio communication.

Then come the waves we are accustomed to regard as radio waves: long waves, from 3,000 to 600 metres;

* In the U. S. A. and other countries of the American continent a. c. networks have a frequency of 60 hertz.



Electromagnetic vibration



...pectrum scale.

medium-frequency waves, ranging from 600 to 150 metres; medium-high frequency waves, ranging from 150 to 75 metres, and short waves, ranging from 75 to 10 metres. The low-frequency boundary of the long waves is 100×10^3 hertz, and the high-frequency boundary of the short waves is 30×10^6 hertz. This entire band is used mainly for radio broadcasting and for various kinds of long-range radio communication. Certain medical units also operate in this band.

The radio spectrum extends further. Yet the horizon line is an almost insurmountable obstacle to radio waves less than 10 metres long. That is why television and radio communications on these wave-lengths are limited to the range of direct visibility. To increase this range, television antennae are set up on very high towers. The wave-lengths of the metre band range from 10 to 1 metre and the frequencies from 3×10^7 to 3×10^8 hertz.

The metre band is followed by the decimetre wave band with wave-lengths ranging from 1 metre to 10 centimetres; the boundary frequencies of this band are 3×10^8 and 3×10^9 hertz. This is the band used by various kinds of radio engineering devices, for instance, radio telescopes, which we shall discuss later. Radio waves of decimetre and smaller lengths have a very interesting feature. They can spread not only through vacuum (through the air) but also through tubes known as wave guides.

Centimetre waves are from 10 to 1 centimetre long (frequency range from 3×10^9 to 3×10^{10} hertz). This band does not differ, in principle, from the previous one. It is used, in particular, by meteorological radar units.

The boundary frequencies of the millimetre radio wave band are 3×10^{10} and 3×10^{11} hertz. At present, millimetre waves are the shortest employed in radio engineering practice.

The radio wave band is followed by the light wave spectrum. The closest to the radio waves is the infrared region, ranging from 400 microns to 760 millimicrons which corresponds to frequencies of from 7.5×10^{11} to 3.87×10^{14} hertz. The waves of this band can be obtained with the aid of special devices, but the simplest method is by merely heating a body of some kind. Conventional incandescent lamps have a very intense radiation in the short-wave infrared

range. Infrared rays are widely used in science, engineering and in the home. They are employed for cooking, heating, and for drying various products. Photographs can be made in these rays and they can be used in special apparatuses for seeing at night.

Visible light rays require no special comment. We shall only remind the reader that they range from 780 to 380 millimicrons in wave-length which corresponds to frequencies from 3.87×10^{14} to 8×10^{14} hertz. Thus we see what a narrow strip of the spectrum of electromagnetic vibrations can be perceived directly by our sense organs.

The ultraviolet ray region begins with waves 380 millimicrons long, which corresponds to a frequency of 8×10^{14} hertz, and extends to wave-lengths of 40 Ångstrom units* and even less. The frequency of a wave 40 ångstroms long is 7.5×10^{16} hertz.

Like infrared rays, ultraviolet rays have found wide application in science and engineering in our days. They are used for detecting various minerals, for delicate chemical analyses, for sterilizing food and medicines. They are also employed in photography, by judicial experts, in light engineering for exciting luminescence in phosphorescent paints. They are widely used in medicine, too.

By the way, ultraviolet rays are incorrectly, but not accidentally, called quartz rays. This is due to the fact that while ordinary kinds of optical glass are opaque to ultraviolet rays of 2,500 Å and shorter, glass made of pure quartz transmits them and, therefore, lamp bulbs of ultraviolet light sources are made of quartz glass.

But even quartz does not allow the entire spectrum of ultraviolet rays pass through it: it is opaque to waves shorter than 1,800 Å. The best material in this respect known at present is fluorite or fluorspar, which transmits rays of wave-lengths down to 1,200 Å.

The next section of the spectrum after the ultraviolet is that of x-rays. The frequency of these rays ranges from 6×10^{15} to 3×10^{19} hertz, which corresponds to wave-lengths

* The Ångstrom unit, or just ångstrom (abbreviated Å) is a unit of length employed in spectroscopy and named after the physicist Ångstrom. It is equal to 0.0001 micron.

of from 493 to 0.1 Å. We are all quite familiar with some of the uses of x-rays. They are employed whenever it is necessary to see through anything which is opaque to other rays. Thus, they are used for detecting hidden defects in metals, for various kinds of research work based on the diffraction of x-rays in the crystals of various substances. Unfortunately, there are no materials in nature capable of refracting x-rays like glass refracts visible rays. That is why no lens-type optical devices can be made for them.

Finally, the last section of the spectrum of electromagnetic vibrations known to science at present is that of gamma-rays. They are emitted by the atoms of radioactive elements; gamma-rays are also produced during some types of interaction between elementary particles. The frequency of gamma-radiation begins at 6×10^{18} hertz which corresponds to a wave-length of 0.428 ångstrom.

It is difficult to indicate the short-wave boundary of gamma-radiation, because it keeps moving off into the region of shorter and shorter waves from year to year. For example, gamma-rays with a wave-length of about 0.0001 ångstrom have been detected in the radiations coming from cosmic space.

The penetrating power of gamma-rays is even greater than that of x-rays. Hence, they are used whenever the latter are unable to pierce the object under study. Besides, all that is needed to obtain gamma-rays is a radioactive isotope, stored for safety in a special container, whereas x-rays are produced only by complicated and cumbersome apparatus. Gamma-rays are also employed in certain chemical processes.

Extraordinary Tails

The biblical prophets devoted most of their attention to all kinds of horrors. Plagues, famines, devastation of cities, the wiping out of whole peoples—such were their favourite prophecies. The prophets used to point to "divine signs" such as rainbows, solar eclipses and other celestial phenomena as omens of misfortune. It is not surprising that "tailed stars"—comets reminding the superstitious of the

Wanderer of the skies — a comet. Its tail is always directed away from the Sun.

chastizing sword—were "put on staff" as heralds of ill-news. And their appearance indeed struck terror into the hearts of religious people. Even today there are still people who believe that a comet is a harbinger of war.

The unusual appearance and comparative rarety of these celestial wanderers in our skies have long since drawn the attention of scientists to comets. A subject of special study was their extraordinary tails. The more so, that their behaviour seemed very strange. The tail of a comet does not follow it, remaining behind the head, but always stays on the straight line joining the comet head and the Sun and points away from the latter.

As far back as the beginning of the XVIII century the famous German astronomer Johann Kepler (1571–1630) put forth the assumption that such orientation of comet tails might be due to pressure exerted by the Sun's rays on illuminated bodies.

Maxwell came to the same conclusion in his theoretical investigations. This was no longer a brilliant conjecture,

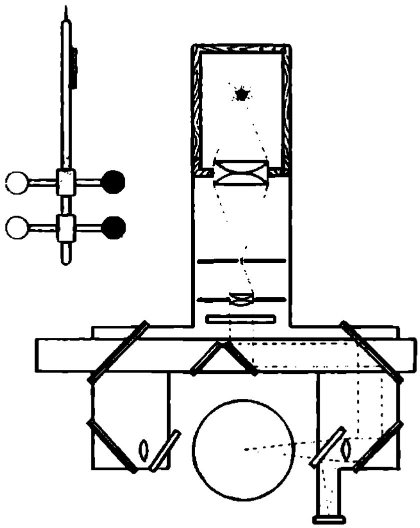


Diagram of Lebedev's apparatus. The axis with the paddles drawn separately was suspended in the glass cylinder. The light of a bright lamp was directed on to the paddles. Under the pressure of the light the axis with the paddles rotated through a certain angle.

but a theoretical thesis supported by exact calculations. Maxwell's calculations showed that perpendicular solar rays exert a pressure of 0.4 milligram per square metre of an absolutely black (perfectly non-reflecting) surface, and of 0.8 milligram per square metre of a specular surface. Of course, the pressure of light depends on the power of the light radiation and on the distance between the light source and the surface on which the rays are incident; the more powerful the source, the greater the pressure; the greater the distance, the smaller the pressure. Therefore, the above figures are not absolute. They were calculated for the case where the light source is the Sun and the distance is that of the Earth from it.

The pressure of light is a fact of fundamental importance to science: it discloses one more important property of light.

That is why experimental proof of these theoretical calculations would be an essential contribution to physics. But the experiment required was very complicated and difficult to carry out, because it involved measurement of extremely small forces.

The first to succeed in making these delicate measurements was a professor of the Moscow University P. Lebedev. In 1899 he measured the pressure of light on solids and in 1909 he solved another still more difficult problem—he measured the pressure of light on gases. This work brought Lebedev world recognition; many universities and scientific associations elected him to honorary membership.

His investigations confirmed the fact of the pressure of light and the accuracy of Maxwell's calculations. On the basis of this fact and Lebedev's work astronomers were able to obtain precise data on the effect of solar light on the tails of comets and even to determine the mass of the particles constituting these tails.

We will recall that the wave theory triumphed over the corpuscular only after such facts as diffraction and interference were experimentally established. These facts could not be accounted for by the corpuscular theory but were in excellent agreement with the wave theory. What can be said of the pressure of light in this respect? It was proved and calculated by Maxwell, who based his electromagnetic theory on the wave concepts of the nature of light, and therefore fully confirms the truth of these concepts. However, the pressure of light is a fact that does not contradict corpuscular concepts either. Moreover, on the basis of Lebedev's experiments an adherent of the corpuscular theory could draw the conclusion that light has mass and even determine the magnitude of the latter!

The Very Tiniest

Science would never have occupied a fitting place if it had not from the very start demanded profound understanding and exact definition of even the simplest, seemingly quite obvious, concepts. For example, here are defi-

nitions* of a white, a transparent and a black body, which would be acceptable to science:

A body which reflects all light rays incident on it is called an ideal white body.

A body which transmits all rays passing through it without absorbing any is called an ideal transparent body.

A body which wholly absorbs incident light rays is called an ideal black body.

Nothing ideal exists in nature. Nor do there exist any bodies which correspond fully to the above definitions, but there are very many bodies that come quite close to them. For instance, certain chemical compounds reflect up to 98 per cent of incident light; not too thick layers of glass or rock crystal are almost ideally transparent over a wide range of light waves; some brands of black velvet absorb up to 99.7 per cent of incident light.

The above definitions would hardly evoke any objections for the simple reason that they are in keeping with our everyday experience. On the basis of such experience we are accustomed to consider a body white if it radiates a lot of light, and black if it does not radiate any at all. The Sun is dazzling white, while an opening in a sooty chimney flue is dazzling black.

At first glance it would seem that our customary idea of black and white does not differ from the physical definition. Actually, however, there is a contradiction. In everyday life we do not notice it because our usage of the verbs "reflect" and "radiate" is not quite correct. We often use one of them to mean the other without noticing the difference. But from the standpoint of physics the difference is essential. And physics attaches a definite functional meaning to each of these words.

To reflect means to throw back, outwards, the rays of an outside light source, incident on the surface of the body in question. Ideal reflection does not change the temperature of the body, nor its stored supply of thermal energy.

To radiate means to give off energy from the body's own supply by emitting rays. On radiation, the temperature of the body, its stored supplies of thermal energy decrease.

* The definitions given are not quite strict.

To keep the radiation from stopping, the energy loss must be compensated for, and this requires some other source of energy. For instance, a dry cell for a flashlight lamp, or nuclear reactions in the Sun.

Then what does the verb "absorb" mean?

In the energy sense, absorption should be understood as the opposite to radiation. On absorption the energy of the body increases, while on radiation it decreases.

Thus, under certain conditions, an ideal white body neither absorbs nor radiates energy. The same can be said of an ideal transparent body. But an ideal black body, being the best absorber of radiant energy, is at the same time the best radiator of energy.

This assertion may seem incredible to the uninitiated. But it is a conclusively established scientific fact. That the Sun is also a black body may sound even stranger to the reader. Yet, if we ponder for a while over the definition of a black body, this will gradually cease to sound paradoxical. As physicists understand it, this statement means only that if rays from any other outer light sources, say, from other stars, fall on the Sun, they will not be reflected, but will be completely absorbed by it.

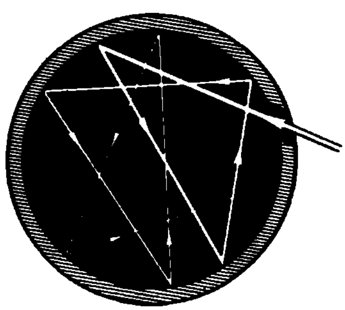
Then, why is it that, far from being black, the Sun is so white that its dazzling rays hurt our eyes? This is so because a fantastic amount of energy is generated in the Sun's bulk, and this energy is radiated into space. About 14 per cent of the solar radiation is visible light. That is what blinds us and that is why the Sun seems white to us. But this by no means contradicts the physical definition of a black body; the definition is concerned only with the absorption of incident rays and says nothing of the radiation of the body's own rays. Thus it is that a black body may be brightly luminous and white, but at the same time it must absorb all rays incident on it from outside light sources. The reader can verify for himself the difference in radiations of heated bodies—white, transparent and moderately dark. To do this, heat a steel nail, an aluminium wire and a piece of glass in the flame of a gas burner. The brightest light will be emitted by the steel, while that emitted by the aluminium and the glass will be hardly perceptible.

It was said above that neither ideal black nor ideal white exists in nature. But for scientific purposes scientists have constructed a device possessing the properties of an ideal black body. And that is just what it is called in physics—a "black body". In design it is a metallic hollow sphere or cylinder with a small opening. Electric heating elements are inserted in the space between its double walls. For better absorption of incident rays the inside surface of the black body is sometimes painted black and roughened.

The part of the black body proper is played by the opening in the sphere. As we know, a black body must absorb all rays incident upon it. The opening exerts the same effect. Now, have a look at the drawing of the device, and you will see that no ray passing in through the opening from the outside, will ever return. It is "entrapped" inside the sphere. Being reflected again and again by the sphere walls, it is partly absorbed each time and is finally swallowed up altogether.

The pupil of our eye seems black for precisely this reason. The same accounts for the fact that in the daytime the windows of houses look black from outside.

We purposely went to such lengths in explaining the properties of a black body. It was necessary because the study of the laws of its radiation led scientists to some very important discoveries. These and certain other facts



Path of a light ray inside a "black body". Each time, on being reflected by the inside wall, part of the light is absorbed, and finally the walls absorb all of the light.

made scientists reconsider once more (for the how many*th* time?) their ideas of the nature of light.

Firstly, it became known that the radiation spectrum of a black body is continuous, i. e., contains vibrations of all possible wave-lengths. Secondly, these experiments revealed that though the radiation spectrum is continuous, the power radiated over different frequencies (wave-lengths) is different: it is maximal inside the frequency (wave) range and falls off practically to zero at its ends; and the higher the absolute temperature, the higher the frequency of the maximal radiation. Thirdly, it was found that the total power radiated by a black body grows as the fourth power of the absolute temperature.

These experimental data were verified many times and could not be doubted. However, when attempts were made to account for them theoretically and derive a formula to describe them quantitatively, scientists came up against unforeseen difficulties which turned out to be of a fundamental nature. All these difficulties stemmed from the fact that theoretical calculations based on the classical theory, which had served so well heretofore, were entirely out of line with reality. According to these calculations, all the energy of a black body should be radiated as short-wave radiations.

This discrepancy between theory and practice made it necessary to draw adequate conclusions. The first to account successfully for the laws of radiation of a black body was the German physicist Max Planck (1858-1947). That was in 1900, three years after the discovery of the electron. However, Planck's main merit was probably not just the explanation of the laws of radiation of a black body, but the entirely new assumption he made in the course of this work.

To get an idea of the singularity of this assumption, it will be useful to carry out a very simple mental experiment. But the reader must bear in mind that the conditions under which it is to be performed are actually not realizable and, therefore, the experiment itself is also impracticable. It can be carried out only mentally.

First of all, suppose we have at our disposal such an accurate measuring instrument that we can measure dis-

tances absolutely exactly and register even insignificant changes in them. The second ideal instrument we shall need is a simple pulley differing from a real one only in that it has no friction.

Now, mentally pass a string over the pulley and tie a weight to one of its ends. Then raise the weight to a height of 1 metre. If the weight was exactly 1 kilogram, then in raising it we had to work against gravity, and did exactly 1 kgm of work. But what does doing work mean? It means spending energy: in this case, 1 kgm of energy. In raising the load we expend energy which is converted into the potential energy of the load raised above the ground. Therefore, the load has received energy. And, since the conditions of the experiment are ideal, it received exactly as much energy as we spent, that is, 1 kgm. Now, we lift the load another 0.000 001 metre. Thus, we spend, and the load receives, another 0.000 001 kgm of energy. Since the instrument we are using to measure the distance is absolutely exact, we could just as well have lifted the load another billionth or trillionth or any other vanishingly small fraction of a metre. The amount of energy expended and received will then also be correspondingly smaller.

Before Planck's work became known, such a purely mental experiment led scientists to the conclusion that energy can be divided into fractions of any degree of smallness, into infinitesimal fractions, in the mathematical sense. On this basis they thought that energy is always a continuous value. Planck renounced this established and seemingly quite obvious and proved idea, considering it inapplicable to radiation processes. He assumed that on being radiated energy can neither decrease nor increase in infinitesimal fractions and that all energy changes can occur only jumpwise, that is, in definite portions, very small, but finite. He called these portions elementary quanta or just quanta.

Suppose we have to fill a measuring glass or cylinder with a definite quantity of a liquid. Naturally, we should not be able to do this quite accurately at first trial: the amount we poured in would be either just below or just above the required division. In both these cases we can either add or remove the necessary amount of liquid and,

practically, we can make these adjustments in portions of any degree of smallness.

Can any quantities be changed so? We know that they cannot. For instance, the number of pupils in a class cannot be increased by 2.7. Nor can sums of money be changed in arbitrarily small fractions. These changes always occur in jumps. In the U.S.S.R. the smallest "jump" in this case is one kopeck, in Germany, one pfennig, in England, one farthing, etc.

This smallest possible change, smallest possible jump in any value is what we call a quantum of that value. Hence, it would be equally right to call a person a quantum if we are talking of the number of pupils at school, workers at a factory, inhabitants of a country and so forth, as to call a kopeck a quantum if we are talking of sums of money in Soviet currency. Obviously, the quanta mentioned have nothing in common. The only thing that gives us the right to call them both quanta is that both values are the smallest possible changes in the respective quantities. There are elementary quanta that can be compared with each other. Such, for instance, are the elementary quanta of the currency of the U.S.S.R., Germany and England, the kopeck, pfennig and farthing, respectively. These are comparable quanta.

In practice many actually discrete values can very well be regarded as continuous. When we weigh grain, sand and other loose bodies, or pour out liquids, we make no perceptible error in considering that their quantities change continuously, that is, in portions of any degree of smallness. Actually, this is not so, and it is commonly known that the mass of loose bodies can change only discretely, though the magnitude of the jump is exceedingly small. We neglect this magnitude in all cases where it is insignificant. But we should do otherwise if we had to weigh valuable loose bodies. We should use a very sensitive and precise balance. And then we should not be able to neglect the fact that the mass changes jumpwise.

The situation is exactly the same when measuring other quantities. When the sensitivity and precision of measurement is increased it often appears that quantities hitherto considered continuous actually can change only discretely,

in jumps, and the magnitude of the smallest, very tiniest possible jump is found to be quite definite and invariable. The mass of water also changes in jumps or quanta. The mass quantum of water is the mass of one of its molecules. Of course, in the great majority of cases this fact may be neglected and the mass of water can be regarded as a continuous value.

But there are other, really continuous values. And no increase in sensitivity or accuracy of measurement would ever show them to vary discretely.

Thus, some values can vary in portions of any degree of smallness, while others can do so only discretely, in jumps, the magnitude of which cannot be decreased. Such an indivisible jump of quantity, such a smallest of all possible portions is what we call an elementary quantum of the value in question.

The electron possesses the tiniest possible negative charge. Hence, the charge of an electron may be called the quantum of electric charge or just the quantum of electricity. Mass also possesses a granular, discrete structure. Thus, the smallest possible mass of hydrogen (as a definite chemical element) is the mass of one of its atoms, equal approximately to 0.000 000 000 000 000 000 000 001 700 g or 1.7×10^{-24} g. Naturally, the quantum of oxygen mass differs from the hydrogen quantum. But their values are comparable because both are expressed in grams of mass.

The same is true for quanta of radiant energy. Their numerical values are different for different wave-lengths. According to Planck's definition, the magnitude of one elementary quantum of radiant energy is given by the formula

$$\varepsilon = h\nu$$

where h = a certain invariable quantity called the Planck constant* after its discoverer;

ν = the frequency of vibrations at which the energy is radiated.

If the radiation of a heated black body is resolved into a spectrum, the latter will contain vibrations with a great variety of frequencies. Therefore, the quanta of the energy

* It is equal to 6.623×10^{-27} erg. sec.

radiated by a black body will also have a great variety of values.

The explanation of the laws of radiation of a black body was the verification needed to confirm the truth of the new theoretical theses put forth by Planck. They are equally true for all kinds of radiation, not only light, but for the entire spectrum of electromagnetic waves, from the longest radio waves to roentgen and gamma-radiations.

But quantum concepts are not employed in radio engineering practice. The magnitude of a separate quantum in the radio frequencies is so insignificant that for practical purposes emitted radio wave energy can be regarded as continuous. By way of example, the numerical value of the quantum of radio waves 3,000 metres long (frequency 100 thousand cycles per second) is 4.4×10^{-10} electron-volts.* That is why the classical electrodynamics built up by Maxwell holds good for radio frequencies.

The granular structure of radiant energy becomes perceptible with light waves. At a wave-length of 1.2345 microns (the near infrared region of the spectrum) the energy of a quantum equals exactly 1 electron-volt. At the red boundary of the visible spectrum it rises to about 2 and at the violet boundary, to 4 electron-volts. Yet, these values are very small compared to 1 quantum of energy radiated in the region of very short-wave gamma-rays. For instance, at a wave-length of 0.007 millimicron the energy of the quantum becomes 1,770 thousand electron-volts. That is the energy acquired by an electron when it is accelerated in the field of a condenser to which a voltage of 1,770 thousand volts is applied.

It must be kept in mind that this energy is radiated by a black body either in such a large portion, or not at all. The same with absorption—either all, or nothing.

In renouncing established, seemingly infallible ideas and formulating new ones, Planck, possibly, did not dream that they were destined to play a revolutionary role in the development of fundamental physical concepts. In the begin-

* 1 electron-volt is the energy acquired by an electron on passing between the plates of a condenser across which a voltage of 1 volt is applied.

ning, at least, he posed quite a concrete problem—theoretical grounding of the laws of radiation of a black body. But no sooner had the first success been scored, than all progressive physicists realized the force of Planck's ideas. They understood that quantum concepts were something much greater than might have been thought at first. They took advantage of the new ideas in studying a very extensive range of phenomena of interaction between radiant energy and substance. And in all cases these ideas helped them to make new progress in penetrating into the mysteries of nature.

The quantum theory developed at an extraordinary pace. It helped to establish relationships between many very important phenomena which had formerly seemed absolutely unrelated. It helped science to discover new wonderful horizons and, in particular, to take one more step forward on the way to understanding the true nature of light. This step was made by Albert Einstein (1879-1955), a physicist of great genius. He was aided not only by Planck's ideas, but also by a very important law established by the Russian scientist Alexander Grigoryevich Stoletov (1839-1896).

The Photoelectric Effect

In carrying out his experiments, Hertz observed incidentally that the spark striking between the oscillator electrodes behaved strangely. Light seemed to affect it. When Hertz illuminated the oscillator electrodes with a strong light the sparks appeared more frequently. As soon as the light source was removed the frequency of sparking immediately decreased. This phenomenon was strange and inexplicable. However, Hertz evidently did not attach much importance to it. Nor is this very surprising, as he had before him an entirely different objective.

But Stoletov, a professor of the Moscow University and an elder comrade of Lebedev, took a greater interest in this observation of Hertz's. He performed numerous experiments, constructed special apparatus for carrying them out, and investigated this phenomenon so profoundly and thoroughly that the results of his work led to a striking dis-

covery. Without it scientists would not have obtained very important information on the nature of light, and modern society would have known neither television, nor phototelegraphy, nor talking pictures, nor many many other very useful technical novelties without which life is now inconceivable.

The phenomenon studied by Stoletov in 1888-1889 is called the photoelectric effect. As a result of his investigations Stoletov established a new physical law which bears his name. Unfortunately, in those years science knew nothing about the existence of electrons (they were discovered only in 1897) and therefore Stoletov could not give the correct physical interpretation of the new law. This was done later, in 1905, by Einstein.

To get a better insight into the photoelectric effect, it is useful to carry out the following comparatively simple experiment.

To do it we shall need an electric battery, a galvanometer or microammeter for measuring the current strength and a special electronic tube called a photoelectric cell. The latter will be the subject of our study. The simplest photoelectric cell is a glass bulb with two electrodes in it. For better performance the electrodes of a photoelectric cell are usually made of special shape. One of them is applied to the inner surface of the bulb as a very thin metal film (consisting of a compound of cesium and antimony or oxygen, of silver and cesium or other elements). The second electrode is a ring of fine wire situated in the central region of the sphere. The first electrode is the cathode, more precisely, the photocathode, and the second, the anode.

Photoelectric cells fall into two large groups. In the cells of the first group as high a vacuum as possible is created inside the bulb; in those of the second, the bulb contains a very small quantity of gas. Photocells of the first group are less sensitive, but possess many other valuable properties.

In our experiment we shall use a high-vacuum photoelectric cell, that is, one which has had practically all the air pumped out of its bulb. Besides, for the sake of convenience, the design of the photocell should be changed so that both electrodes are flat plates of exactly the same size

and made of the same metal. Such a photocell is shown in the diagram of our experiment.

Connect the negative terminal of a battery to one of the electrodes and the positive terminal, via galvanometer, to the other. Then the former (negative) electrode will be the cathode, and the latter (positive), the anode. Place the photocell in a dark box. The galvanometer indicator will stand stock-still at zero. But if we open the box cover a little, it will be deflected to the right. The more light enters the box, the more current will flow through the photocell, and the more the indicator of the galvanometer is deflected to the right. By further varying the conditions of our experiment, we find that it is by no means necessary to illuminate the whole photocell to make the current flow. The light ray need fall only on the cathode, rather on the surface of the cathode facing the anode. Moreover, if we illuminate only the anode, leaving the cathode in the dark, the indicator will remain in the zero position.

But the only difference between the cathode and the anode in our experiment is that the latter is connected to the positive pole of the battery, while the former is connected to the negative pole. That is why the current flows only when we illuminate the cathode. But if we reversed the battery connection, what is now the cathode would become the anode and vice versa. Hence, if we were then to illuminate what was formerly the anode we would make the current flow, would we not? Yes, that is exactly what would happen.

Now let us suspend our experiment for a while and think over the results. We have established the following important facts:

1. Light incident on the cathode causes current to flow through the photocell.

2. The current flows through the photocell only in one direction, from cathode to anode (we mean the actual and not the conventional direction).

3. The more light incident on the cathode, the greater the current.

In order to account for these facts, that is, to give them a theoretical grounding, we must recall three other facts well known to science:

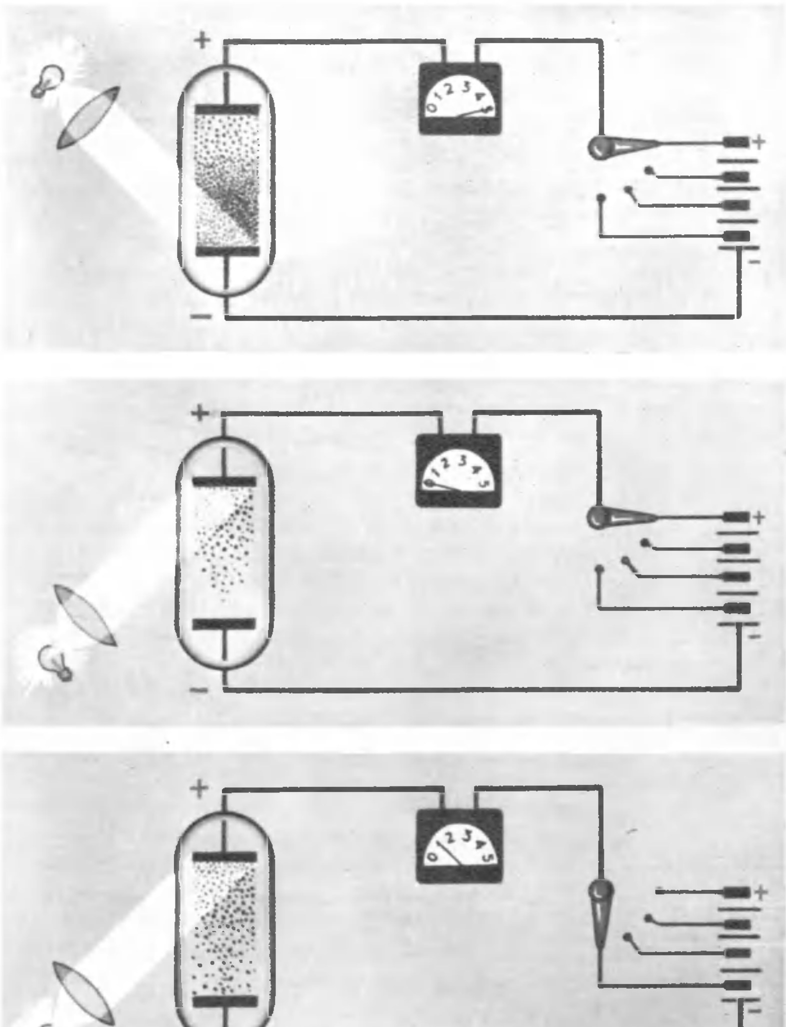


Diagram of experiment with photoelectric effect: 1—when the cathode is illuminated the meter shows that a fairly strong current is flowing through the circuit; 2—when the anode is illuminated there is no current in the circuit; 3—the voltage in the circuit is greatly lowered. When the anode is illuminated the meter shows that a weak current is flowing.

1. Electrons are contained in all substances. They are retained in them by specific forces of attraction.

2. Electrons are negatively charged.

3. Like electric charges repell, while unlike electric charges attract each other.

Knowing all this, we can get an insight into the processes occurring during the photoelectric effect. Indeed, as it has been firmly established that current flows through the photocell from the cathode to the anode, in other words, from minus to plus, it may be concluded that the carriers of the current are electrons. But where do they come from?

Our experiment showed that current flowed only when the cathode was illuminated with light. Hence, light acts on the cathode in such a way that the latter begins to emit electrons. Moreover, the more light incident on the cathode, the more electrons emitted. Now, how does light act on substance to make it liberate its "prisoner" electrons?

A stone thrown upwards will fly the higher, the greater its velocity, the greater the energy it received on being thrown. But no matter how high it flies, it will always return to the Earth: it is forced to do so by the Earth's gravitation. But we know that if we impart to a body (so far, only a rocket, not to speak of elementary particles) a velocity of about 8,000 metres per second and, consequently, the corresponding energy, it will not return to the Earth but will become its satellite. If the initial velocity of a body exceeds 11,200 metres per second it will go beyond the limits of the Earth's gravitation.

A similar thing happens to electrons. On penetrating into substance, light gives its energy away to the electrons in it. This additional energy raises the velocity of the electrons. If the new velocity is greater than a definite value for each given substance and the motion of the electrons is outwards from the substance, the electrons will leave the substance and "rise" above its surface. The more energy the electrons receive from the light rays, the higher their new velocity and the farther they will fly from the cathode towards the anode.

They say that Johann Kepler would not have been able to establish the laws of motion of the planets if the observations made by the Danish astronomer Tycho Brahe and by himself were more accurate. Fortunately (strange as it may seem), the instruments at the disposal of both scientists had not reached the degree of perfection where they could notice the irregularities in the motion of the planets, which in those days might have led the scientists into confusion and kept them from discovering these most important laws.

In the experiment with the photocells we also employed a rather insensitive instrument. When we reversed the connection of the battery, we observed no current and, considering that there was no current at all, we drew some very important conclusions from this. However, actually this is not so. We did not detect any current because it was very small and could not be detected by such a crude instrument as we used.

Now let us repeat the experiment using a much more sensitive instrument. We shall call the electrode, on which the light rays are incident, the cathode, though the positive pole of the battery be connected to it. Switch the unit on and lower the voltage applied to the photocell, observing the readings of the instrument. The voltage is measured with an ordinary voltmeter. If it was minus 10 or 20 volts at the beginning of the experiment, we should not detect any current, no matter how sensitive the instrument. But when the negative voltage is reduced to a few volts, the indicator of the instrument measuring the current intensity will deviate from zero. We shall find, moreover, that electrons move towards the anode though a negative voltage has been applied to it. The smaller the absolute value of the negative voltage, the stronger the current.

To account for this rather unusual fact it will be useful to recall the behaviour of a stone when it is thrown upwards. It has already been said that the greater the initial velocity of the stone, the larger its supply of energy, the higher it will fly. But whatever its initial velocity, provided it does not exceed 8,000 metres per second, the stone will be sure to return to the Earth. Now, what would happen to it if an immense celestial body suddenly appeared at a certain

comparatively small distance from the Earth? In this case the stone might not return, even if a much smaller initial velocity had been imparted to it. Its fate now would depend not only on the Earth's gravitation, but on the gravitation of the other celestial body as well. The larger the latter force, the smaller the initial velocity that would be required for the stone to leave the Earth forever.

Suppose the new celestial body did not attract the stone when it was thrown upwards, but repelled it. Could the stone reach its surface in such a case? Yes, it could. To overcome such a barrier, that is, to do the necessary work against the repelling forces, it would have to be given the required amount of energy or, which is the same, the required initial velocity at the beginning of its flight.

In this mental experiment we made an absolutely fantastic assumption concerning the existence of a celestial body close to the Earth which, moreover, repells bodies that come close to it instead of attracting them. Of course, it is not worthwhile making such fantastic assumptions at a whim, but if they are likely to be of use, physicists never hesitate to make them. In our case, the use is that we followed in fairly vivid form processes that are close to those actually taking place in a photoelectric cell.

Indeed, when we apply a negative voltage to the anode we retard the electrons which have flown out of the cathode and make them turn back. And, conversely, in doing the "regular thing", that is, in applying a positive voltage to the anode, we help the electrons to leave the cathode.

If, beginning at zero, we gradually increase the positive voltage, the current flowing through the photocell will grow even though the light flux incident on the cathode remain constant in value. This happens because as the positive voltage rises, the force of attraction of the electrons to the anode also increases, and electrons with ever smaller initial velocities will be able to reach its surface. However, the current will not grow indefinitely. At a certain voltage it will have reached a maximum and after this will change no longer, no matter how much we increase the voltage. This is natural: the force of attraction to the anode becomes so great that even the "laziest" electrons do not return to

the cathode. Further increase of this force will not increase the current. The current flowing in this case through the photocell is called the saturation current. It must not be forgotten that according to the law of Stoletov the value of this current is the higher, the greater the light flux incident on the photocathode.

Now it will not be difficult to understand the case where the battery is switched on in reverse. The anode then plays the part of the repelling heavenly body, and the higher the absolute value of the negative voltage, the greater the force of repulsion. In this case far from every electron will reach the anode. Only the fastest, the most energetic of them will overcome the barrier. As the negative voltage grows, the number of such electrons will steadily decrease and will finally become zero—and current will cease to flow through the cell.

Knowing the value of the negative voltage between the anode and cathode physicists can calculate the initial velocities or initial energies of the electrons that overcame the forces of repulsion. This energy is expressed in electron-volts. Thus, if an electron overcame the forces of repulsion that arise at a difference of potentials between the anode and cathode of 5 volts, this means its initial energy was not under 5 electron-volts. Varying the value of the negative voltage between the anode and cathode and measuring the current each time, we can easily find the number of electrons which received a definite initial energy at any given illumination.

Now we can approach the decisive stage of in vestigation of the photoeffect. What would happen if instead of white light, which is a mixture of rays of different wave-lengths, we illuminated the cathode with monochromatic light, all the waves of which have practically the same length?

By the time this experiment was first performed, the wave theory had held its ground firmly for about ninety years. During these years more than one generation of physicists had come and gone and none of them ever doubted its absolute authenticity because all new discoveries in the field of optics were always successfully interpreted in terms of wave conceptions. What was the surprise, no,

bewilderment of scientists when they heard of the results of investigation of the photoeffect with monochromatic illumination! They contradicted what had hitherto been considered beyond doubt.

First of all, it turned out that light of not any wave-length knocked electrons out of the photocathode. The shorter the wave-length of the incident light, the more readily did the electrons leave the cathode. By applying negative voltages of various magnitudes to the anode of the photocell, it was found that the energy of the emitted electrons and, therefore, their initial velocity remains constant when the intensity of the light is altered, and depends only on the wave-length. The bluer the light rays became, that is, the shorter the wave of the incident light, the larger the negative voltage that had to be applied to the anode to stop the photocurrent completely. And, conversely, the longer the waves of the incident light were, the smaller the energy of the liberated electrons. Moreover, when the wave-length of the incident light reached a certain value the photoeffect ceased, no matter how much the incident light flux or the anode voltage was increased. The ultimate wave-length at which photoeffect ceases is called the red boundary of photoeffect. It differs for different substances. A great deal of work had to be done to raise the red boundary, to move it out into the region of long light waves. In our days photocathodes have been designed having red boundaries at a wave-length of 1.2 to 1.6 microns.

From the wave theory it followed that the energy of electrons torn out of the cathode by light should increase with growing light flux. Experiment revealed a different regularity: when the light flux is increased the energy of the electrons emitted by the photocathode does not change, but the number of electrons grows. The energy of the electrons leaving the photocathode increases when the wave-length of the incident light is shortened.

After the discovery of the photoeffect, scientists were again obliged to turn to the essentials of physical optics and to seek the answer to the fundamental question: "What is light?"

Interlude

Before finishing this chapter let us now have a little recess to review what we have read and to recall the main things we have learned about light.

1. Development of optics before Newton.

At this stage no more or less trustworthy theories of light had yet been created. Nor had a sufficient amount of facts been accumulated, though such optical instruments as lenses, concave mirrors and even microscopes and telescopes had already been invented.

Grimaldi published his work, in which no profound theoretical ideas were put forth, but the phenomena of diffraction and interference were mentioned for the first time, though in very approximate form.

2. Newton.

His works were a veritable epoch in optics. He discovered new facts and on their basis formulated very important laws of optics and formed the first really scientific theory of light. According to this theory light consists of a specific kind of material particles called corpuscles. This theory explained all known facts well enough, except one phenomenon discovered by Newton, called the Newtonian rings (and, of course, except interference and diffraction, which were unknown to Newton).

3. Huygens.

Velocity of light determined by Ole Roemer.

Huygens built his theory a little later than Newton. According to Huygens's theory light is not a material body, but waves propagated through a specific kind of matter called universal ether.

4. Domination of the corpuscular theory.

Huygens's theory could account for all the facts known at that time, including the Newtonian rings. Yet, after the death of Newton and Huygens the corpuscular theory predominated.

5. Domination of the wave theory.

At the turn of the nineteenth century the wave theory scored a complete victory by explaining the phenomena of interference and diffraction. The existence of ether was universally recognized, though scientists could not perform a

single experiment by which ether could be detected directly. The chief evidence in favour of ether was the fact of the propagation of light waves.

The latter decades of the XIX and the beginning of the XX century were marked by a whole series of very important discoveries in physics, including optics. The theoretical works of Maxwell and the experiments of Hertz made it possible to establish the electromagnetic nature of light waves. Stoletov formulated the laws of the photoeffect. In explaining the laws of radiation of a black body, Planck came to the conclusion that the energy of light is not radiated continuously, but only in definite portions depending on the wave-length of the radiation. These portions he called quanta. Further investigation of the photoeffect led to an unexpected discovery: the energy (velocity) of a photoelectron knocked out of a metal by light does not depend on the intensity of the light, but only on the wave-length of the light incident on the photocathode. The shorter the incident light wave, the higher the energy (velocity) of the electron.

The latter discovery contradicted the wave theory of light.

After the Crisis

The discoveries described were not the only ones made at the turn of our century. The number of new facts disclosed in those years by physicists was especially large. Many of the new facts were of importance not only in a particular field, but struck at the very foundations of science.

There is no need to enumerate all the discoveries of those times. Suffice it to say that they laid the basis for the present-day upsurge of physics. It would seem that these discoveries should have inspired scientists to new, still more energetic searches. And, of course, so they did. But at the same time it all proved very difficult and involved.

The new discoveries did not fit in with the recognized theories which had already been worked out in detail and verified by experience, the theories that many scientists considered infallible and even absolutely correct. And now

these theories fell to ruin before their eyes. Many scientists considered that the new facts left no stone unturned even in the magnificent edifice of classical mechanics. And some scientists, seeing what was happening and unable to account for it plausibly, even voiced the opinion that no correct theory could be built at all, that all theories, no matter how good they were, were nothing but a creation of the mind and did not, and could not as a matter of principle, reflect the phenomena of the world around us correctly.

Those were troubled times, and they have earned the name of the crisis of physics. In his classical work "Materialism and Empiriocriticism", in the chapter entitled "The Latest Revolution in Natural Science and Philosophical Idealism", V. I. Lenin shows how deep-seated was this crisis, how painful the breakdown of old ideas in the minds of many physicists.

Fortunately, all prominent scientists possess a very important quality, which can be described by the single word "fearlessness". Fearlessness before facts, whatever they are. This quality has brought the majority of them to the right conclusions and has helped them come out of the most difficult situations and develop science further. In doing so they have always consciously, and at times subconsciously, sided with the only true philosophical basis of science, with materialism.

And that is just what made it possible to put an end to the temporary perturbation that reigned in the minds of physicists during the crisis. When it was already a thing of the past, it became clear that physics had undergone a real revolution.

Maxwell finished his famous "Treatise" in 1873. In it he proved light to be an electromagnetic phenomenon. But this was far from all. Though Maxwell himself in building up his theory proceeded from the idea that ether existed, his theory was no proof of its existence. *His theory did not clash with the standpoint that light needed no medium for its propagation,* because one of the properties of electromagnetic vibrations is their ability to sustain themselves and thus to travel through absolute vacuum. In other words, the ether hypothesis could be scrapped. However, this aspect of Maxwell's theory was not quite clear even to its author.

Maxwell's theoretical ideas were confirmed by direct experiment only in 1888. But the first staggering blow was dealt to the ether hypothesis much earlier, in 1881.

Physicists did not realize at once that Maxwell's theory remained valid without the ether concept and continued to believe in its existence. Such were the Dutch physicist Hendrik Antoon Lorentz (1853–1928) and Hertz. The same Hertz who was destined a few years later to confirm the truth of Maxwell's electrodynamics. Both Hertz and Lorentz built each his own theory to explain the interaction between electromagnetic vibrations and ether. The chief difference between these theories was the following: Hertz believed that moving material bodies entrained ether, while Lorentz was an adherent of the idea of stationary, immobile ether.

The Hertz theory did not find wide recognition, because by the time it was put forth verified experimental data were known that contradicted it. As to the Lorentz theory, it was more perfect and did not disagree with the experimental data known at the time. But it had to be verified in its main point. It stated, for instance, that the velocity of light radiated in the direction of the Earth's motion would differ from that of light radiated at right angles to this motion.

But such an experiment was not easy to carry out. The accuracy required had to be unusually high. This was due to the fact that the velocity of the Earth in space is not more than one ten-thousandth of the velocity of light. Yet, the experiment was performed. The first to succeed in this was an American professor in physics Albert Abraham Michelson (1852–1931). The results of the experiment showed that the velocity of light is independent of the direction of movement and the velocity of the light source.

Michelson's experiment was a death blow to the ether hypothesis.

Even if the consequences of this experiment were limited to these conclusions, they could be regarded as extremely important to science. But the consequences were far more important: the fact established by Michelson made physicists review all classical mechanics, the laws of which, as it turned out, hold good only for low velocities.

No wonder, therefore, that in 1887 Michelson repeated the experiment again together with the physicist Morley, and subsequently, for many years it was repeated again and again with greater and greater accuracy by numerous scientists. Perhaps some of them did it hoping secretly to refute previous results. But the velocity of light was invariably found to be constant.

Scientists understood what serious consequences could result from this fact. They saw that it was not only undermining the theories themselves, but was breaking down the very foundations of their world outlook, a world outlook that had been pieced together through the centuries.

The way out of the situation was found by Einstein. In 1905 he published what is known as the Special Theory of Relativity.* The postulates and formulas of this theory brought out an extraordinary picture of the world around us. In this world time was no longer the general pulse of the boundless Universe. Hours changed their rates depending on the velocity of movement. This world knew no constant dimensions: the same moving body had different sizes for different observers. And even mass—a thing that had seemed stable, invariable and non-vanishing—acquired new unexpected properties: it also depended now on the velocity of the body. And, what is no less important, mass was found to possess tremendous latent supplies of energy. Mass and energy could no longer be considered separately from one another, because a direct relationship had been discovered to exist between them.

This new, fantastic picture of the world, which the mind still finds difficult to grasp, reflected the real world far more accurately than that drawn by physicists of previous generations. Fortunately, the newly discovered features did not contradict the old, but supplemented them and came to the fore only at velocities comparable with the velocity of light. At ordinary velocities these new properties could not be detected even with the aid of very sensitive instruments;

* Later he developed the General Theory of Relativity, which deals, among other things, with the geometrical properties of space and the nature of gravitation.

and the world again became the good old, cosy Newtonian world. Classical mechanics remained the law-giver in it as before. But now scientists knew the boundaries of its realm: it remained valid only at velocities much smaller than that of light. When the velocity of bodies became comparable with the velocity of light the new laws discovered by Einstein had to be used.

The Theory of Relativity was one of the greatest triumphs of the human mind, and no wonder world fame followed the prominent physicist and thinker throughout his life. But Einstein created not only the theory of relativity. In the same year (1905), on the basis of Stoletov's law and the work of Planck, mentioned above, he explained the phenomenon of photoeffect and thus laid the foundation for a new understanding of the processes of interaction between light and substance. Had Einstein done nothing else for science in his whole life but derive the formula of the photoeffect and its interpretation, it would still have been enough to make his services to science no less valuable than those of many scientists whose names have gone down in the history of physics forever.

To distinguish the quanta of light energy from other quanta they were named photons. The energy of the photons (or the magnitude of the quanta of radiant energy) varies depending on the wave-length of the radiated light. At the same time, it is strictly constant for any given wavelength. We will recall also that investigations of the photoeffect revealed that the velocity of an electron knocked out of the photocathode depends only on the wave-length of the incident light and is independent of its intensity. This fact was in complete contradiction with the wave theory, in particular, with the mathematical definition of the energy of light, which followed from this theory.

In explaining the phenomenon of photoeffect, Einstein denied the wave theory. He understood that no artificial constructions could save it. He took another path suggested, possibly, by the wonderful community between the facts of the radiation of energy by a black body and the facts observed when studying the photoeffect.

Here are these facts which we already know:

1. The energy (or velocity) of an electron torn out of

the photocathode by monochromatic light of invariable wave-length is always the same. The shorter the wave of the incident light, the higher the energy (or velocity) of the electron.

2. The energy of a radiated photon is always the same for an invariable wave-length. The shorter the wave-length of the radiated light, the higher the energy of the photon.

And here are the conclusions drawn by Einstein on analyzing these facts:

1. The energy of a photon which has penetrated into the substance of the photocathode is transferred wholly to only one of the electrons in the substance of the photocathode.

2. A rise in energy of the electron, manifested as a rise in its velocity, will result, provided the energy of the photon is large enough, in ejection of the electron from the photocathode. The higher the energy of the photon, the greater the energy (velocity) of the emitted electron. In terms of the wave theory this would be: the shorter the incident light wave, the higher the energy (velocity) of the electron torn out of the photocathode.

3. The higher the intensity of the light and, therefore, the more photons per unit time incident on the photocathode, the more electrons knocked out of it, that is, the larger the current.

These are the conclusions on which the explanations of the photoeffect are based. They enable not only a qualitative, but a quantitative theory of this phenomenon to be created.

However, this is far from all. The definition of a light quantum—photon—given by Planck was purely mathematical and said nothing about the physical essence of the photon; it only described its energy. Before Einstein nobody could say how the photon behaved in space, or how it should be visualized, even approximately. Einstein's Theory of Relativity helped him to explain the photon concept.

One of the important conclusions of this theory states that the photon possesses mass. True, in contrast to ordinary bodies, the photon has no rest mass. It cannot be thought of as stationary; it can travel through space only at the velocity of light, for it is light, rather, a particle of it.

But it is not the Newtonian corpuscle which was imagined as a very minute grain, as an absolutely elastic body and which could very well be pictured stationary in space and invariable in time. No, the photon is nothing like that: it is all in motion, it cannot exist outside of motion.

Yet, despite these extraordinary properties, many indications gave scientists the right to class the photon as a particle and, hence, to revise their ideas of the nature of light once more. In our days light is no longer considered a wave phenomenon in the classical sense of the word.

Then, what is to be done with the wave concepts? Is the wave theory altogether incorrect and, therefore, ought to be discarded? Fortunately, not. The wave theory *ought* not to be discarded, moreover, it *cannot* be discarded, for it continues, as before, to reflect and explain correctly a large number of facts, a great variety of light phenomena. But not all. We know now that the wave theory, though correct, is not all-embracing. In other words, it is not a universal theory because it is not able to explain, for instance, such a phenomenon as the photoeffect. Nor was the theory of light, which Einstein helped to build, universal. The new corpuscular or quantum theory explained the photoeffect and some other phenomena and even forecast certain important facts, but scientists came up against insurmountable obstacles when they tried to account for interference and diffraction phenomena in terms of the new theory.

Such was the situation in optics after the advent of the new theory of light. In some cases scientists were obliged to resort, as before, to the wave theory, in others, they had to apply new ideas, the new theory. True, there was no "unbridgeable gap" between the two theories; there were many facts, such as the pressure of light, which did not contradict either theory. And this brought the hope of forming such a theory which would be equally applicable to interference and diffraction, on the one hand, and to the radiation of a black body and the photoeffect, on the other.

Indeed, in the subsequent years of rapid progress much was done to interpret and eliminate this duality of theories, this ambiguity in the understanding of the nature of light.

In those years scientists discovered the astounding fact that, like light, the electron could in some cases be treated as a particle, and in others as a wave. In other words, they discovered that under certain conditions the electron behaves like a wave.

The length of the wave associated with the electron depends on its velocity. The higher the velocity, the shorter the wave-length. Thus, when an electron is accelerated in the electrostatic field of a condenser across which a voltage of 25 thousand volts is applied, the length of the associated wave is 0.0075 millimicron or 7.5 Ångstrom units. ***When an electron in motion encounters a small obstacle, comparable in size with its wave-length, it undergoes diffraction, just like light.*** Is this not the most obvious proof of its wave properties?!

The exhibition of such seemingly contradictory properties by the electron confirms the brilliant statement of V. I. Lenin, who wrote in his "Materialism and Empiriocriticism":

"The 'essence' of things, or 'substance' is *also* relative; it expresses only the degree of profundity of man's knowledge of objects; and while yesterday the profundity of this knowledge did not go beyond the atom, and today does not go beyond the electron and ether, dialectical materialism insists on the temporary, relative, approximate character of all these *milestones* in the knowledge of nature gained by the progressing science of man. The electron is as *inexhaustible* as the atom...."

This statement of Lenin's is sometimes understood as a direct indication that the electron is divisible in the mechanical sense. Evidently, there are no grounds now to deny the possibility of such a division at some time in the future. But this is not what Lenin meant; he was talking of the inexhaustibleness of the electron as an object of man's cognition. And the truth of his words is now excellently confirmed by what is already known about the electron. Discovered as a ray, it afterwards became known as a particle, and then was found to possess wave properties. And the deeper we penetrate into the mysteries of nature, the more different properties shall we discover in the electron.

This refers also in full measure to our knowledge of light. The present-day level by no means exhausts the development of the physical conceptions of light. They will continue to grow richer and more profound as long as physics itself continues to advance, for light is one of the most important objects of this branch of science.

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And so, our story of the nature of light has come to an end, or, rather, we interrupt it at the point where we should have passed over to the latest, much fuller and more accurate ideas of the nature of light. The story could have been continued, but we shall not do so in this book.

Here is why:

First of all, because the present-day theory of light deals with conceptions which differ radically from the conceptions and phenomena we can perceive directly with our senses. When talking about modern conceptions of the theory of light the Soviet physicist Academician S. Vavilov (1891–1951) pointed out that they cannot be imagined or described in so many words: they can be described only in the language of mathematics.

"Our mechanistic conceptions," he wrote, "are incapable of grasping reality in full, for lack of graphic images."

Besides, the present-day stage of development of the theory of light is far from complete as yet, and this makes its popular exposition still more difficult.

We might mention only that physicists have succeeded, to a considerable extent, if not completely, in creating a unified theory of light which can equally well account correctly for all the phenomena known today in the field of optics. This theory has at the same time enabled scientists to get a much deeper insight into the nature of light.

It must be emphasized once more that the present-day stage in the development of the science of light is far from complete. Therefore, with the discovery of new facts owing to the perfection of experimental techniques, with the development of new and better theoretical methods, our understanding of light will become ever deeper and more accurate.

It must be kept in mind that the stage of development optics has reached today is not its last. It is known that no absolute theory can be built. Everything the reader has learned here bears this out. But the struggle of theories, keen though it may be at times, does not signify by any means that each theory must die out completely sooner or later to be replaced by another theory which is also doomed. It would be wrong to understand the history of science in this light.

Indeed, if you look back now you will find that though the corpuscular theory died, it did not disappear altogether. It came to life again, this time on the basis of an immense amount of new knowledge. The revived theory did not abolish the wave theory, but just supplemented it. The new theory of light made use of both these theories. Though differing in many respects from its predecessors it did not discard but combined them. At the same time, the new theory defined the boundaries of applicability of the old ones, so that they can be used within these boundaries with even greater confidence than before the boundaries were known.

A similar thing happened to classical mechanics. At first it was the only one in the field and because of that nobody knew the boundaries of its validity. Then a mechanics appeared based on the Theory of Relativity. This did not mean at all that classical mechanics was not true. It is correct, but not all-embracing. It is not impossible that the same will happen to the Theory of Relativity. In time it may also be replaced by some new, now unknown theory. But the Theory of Relativity has been confirmed by so many facts that it can never be discarded as absolutely wrong.

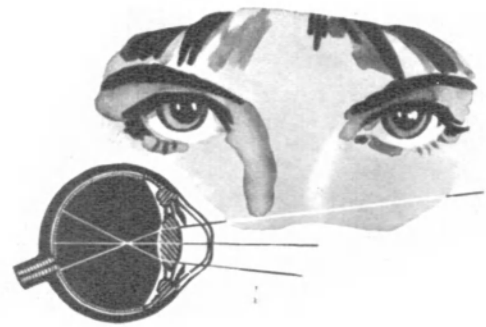
At present criticism of this theory is already voiced in some quarters. And some scientists, even such a famous one as Paul Dirac, have again raised the question of the existence of a certain universal medium, which in some respects resembles ether. It is difficult to say how much truth there is in the present-day criticisms, or how well grounded Dirac's standpoint is. Truth, as we know, is born in argument. Science only benefits from arguments concentrated on its key problems but it loses when ungrounded

criticism is brought into play. This should be remembered by our readers, some of whom, perhaps, are destined to have their say in physics.

The second reason why we cannot dwell in greater detail on the present-day stage of development of optics is much simpler. If this unfinished story has been understood by the reader, there is no great harm in its being unfinished. In this book, the history of development of views on the nature of light was interrupted not just arbitrarily. The state of the art at which we broke off our story corresponds to the understanding of the nature of light predominant today in all branches of science and engineering where light is widely used, but not investigated.

In other words, today it is still quite legitimate to regard light as either a wave or a quantum phenomenon, depending on the field of its application. Thus, in developing optical systems for microscopes, telescopes, photocameras and so on, only the wave theory of light is used, while in developing instruments based on the photoeffect, the starting point is the quantum theory of light.

This is just how the reader should regard light. Such a standpoint will not be out of date in practice for many years. Recent remarkable achievements in the practical applications and uses of light show how fruitful this standpoint is. The following chapters deal with these achievements.



THE EYE AND VISION

The study of nature must necessarily involve the study of the human senses as well. In order to be accurate in our observations of light and colour in the landscape we must first of all be familiar with the instrument we use continually — namely, the human eye.

M. MINNAERT

Prelude

When we come to think of it, each sense organ of the higher animals and especially of man is really a wonder. The ability to hear and analyze sounds, to perceive and distinguish between an immense variety of odours and to determine their significance involves such complex and delicate processes that despite the tremendous progress of science and engineering we are still unable to reproduce them in any artificial instrument or apparatus. But neither hearing nor smell can compare with vision in this respect. Vision is the most perfect, the most fruitful means of cognition. No wonder the saying goes: "To see once is better than to hear a hundred times."

The possibilities of vision depend not only on the proper-

ties of the eye, they are determined also in many respects by the brain, with which the eye is connected.

Unfortunately, science as yet knows little about the vision processes which take place in the brain. It is impossible just now even to conjecture the consequences of the very important discoveries that await mankind in this field.

For ages man has strived to perfect his eyesight, to adapt it for work under new and ever more complex conditions. In the centuries that have passed since optics was born and began to develop, a great many simple and complex instruments have been created, which make it possible to see and observe in cases where the naked eye is quite helpless.

In our times man's vision embraces interstellar space and virus particles of vanishingly small size; it penetrates the body of metals, it covers immense distances and pierces the ocean depths. At present almost the whole spectrum of electromagnetic vibrations, from gamma-radiations to the longest radio waves has been put more or less extensively at the service of man's vision. A large number of different devices have been invented for this purpose and are continually being perfected. These include: roentgen (x-ray) equipment, various kinds of microscopes, binoculars and telescopes, light converters and amplifiers, radar, radio-telescopes and many other interesting apparatuses.

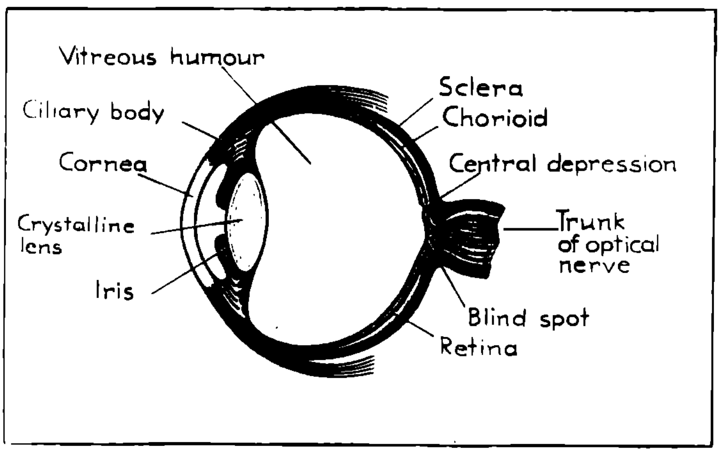
All these new possibilities of vision could and can be discovered only on the basis of an extensive knowledge of the nature and laws of light, as well as the properties of the primary source of vision, our eye. The deeper our insight into these things, the more formerly inaccessible fields are opened to our observation.

Our Eyes

It is often said that nature is the best inventor. This is true. But it might be added that nature likes to repeat itself and does not strive to solve complex problems in new ways each time. But the solution is always the best possible, because it invariably obeys the law of natural selection.

Indeed, despite the great variety of species of higher animals inhabiting the firmament, their eyes bear a great resemblance to each other. In everyday life we mostly distinguish people's eyes by their colour: green, grey, brown, blue, black. But this is only a difference of appearance: a blue-eyed person does not see the world in a blue light, nor a black-eyed person, in a black light. The eyes of all people irrespective of race, sex, etc., have exactly the same structure and see exactly the same, too. Moreover, they have very much in common with the eyes of other mammals and even birds, for the organs of vision of all of them are built up of very similar basic elements.

The eye of man, held snugly and reliably in a bony concavity of the skull, is a nearly spherical body about 24 millimetres in diameter. It has a tough fibrous outer coat called the sclera. We call its visible part, resembling a delicate glazed porcelain decorated with a fine pattern of blood vessels, the white of the eye. In the front part of the eye the sclera changes shape, becoming more convex, more curved. Also, instead of being white and opaque to light it becomes transparent here, and this part of it is



Section through human eye.

called the cornea. It is here that the light rays enter the eye. The inner surface of the sclera (except the cornea) is lined with the second layer of the eye's shell, a highly branched network of minute blood vessels, called the chorioid. In the region of the cornea this coat becomes the iris with a black round opening in its centre, known as the pupil.

Though the iris is the most beautiful part of the eye (and, possibly, one of the functions assigned to it by nature was that of an ornament), its main purpose is not to make the human eye good to look at. It plays a very important part, helping the eye to adapt itself to various conditions of illumination. Everybody knows (and this is easy to verify if a mirror is available) that the pupil becomes very large in the dark and eyes of any colour seem to be quite black, because the iris contracts into a narrow ring which is hardly visible from afar. On the other hand, in bright light the pupil contracts. Scientists have measured these changes of the pupil: in the dark its diameter may be as large as 8 millimetres, while on a bright sunny day it contracts to 2 millimetres.

Those who go in for photography know that camera lenses are furnished with a device that greatly resembles the iris of the eye and is accordingly called an iris diaphragm. The purpose of these two devices is identical: both serve to control the amount of light entering the eye or falling on the light-sensitive layer of the photographic film.

The aperture of the pupil is controlled by the brain, but this takes place subconsciously, owing to a specific reflex. We do not notice or feel the process, though it is going on continuously. It is interesting to note that the pupil continues to contract and dilate slightly even after a person has been kept for a long time in a room with only artificial light. When it is day outside the pupil of the examinee contracts, and at night it dilates, though the conditions of illumination are kept constant throughout the experiment.

Behind the iris is the crystalline lens, an elastic transparent double-convex body representing a converging lens. It is located in a special transparent capsule surrounded by an annular muscle called the ciliary body. When it is

relaxed the surface of the lens is the least curved. Contraction of the ciliary body makes the lens alter its shape and the convexity of the lens becomes greater.

The space between the cornea and the front of the crystalline lens is filled with the aqueous humour. This is a transparent liquid thought to form as a result of very fine filtration of the blood.

The structure of the crystalline lens is rather complicated. It consists of several lenses one inside the other. Their optical properties are not identical: the inside ones refract light more strongly than the outer. The cornea and the crystalline lens together make up the optical system of the eye; they fulfil the same function as the lens of a photographic camera. The image in the eye, produced by the lens together with the cornea, is inverted just like in a camera. This "defect" of the eye is corrected by the brain. The sections of the brain which govern vision adjust themselves in early childhood so that the visible world takes an upright position.

To obtain a good snapshot we must focus our camera, that is, get a sharp, distinct image on the emulsion. We do this by moving the lens along its longitudinal axis. If the object is very far off (in practice, more than from 50 to 250 metres away), the distance between the lens and the emulsion should be the smallest. If a close object is being photographed, the lens should be moved farther away from the film.

Thus, if the lens has a focal length of 5 centimetres, to obtain a sharp picture of an object located 25 centimetres away from the camera the lens must be moved forward. If it was initially in the position corresponding to a focus for infinity, it should be moved forward 1.25 centimetres, that is, exactly 1/4 of the focal length.

When threading a needle we hold our hands out at a distance of about 10 or 15 centimetres from the eyes. And then the tiny opening and the end of the thread can be seen clearly and distinctly. When we enjoy the moon or the setting sun these objects are an immense distance away from us. Yet, they are perceived just as sharply and clearly as the needle's eye. This is because the eye also focusses, but it does so automatically. The ability of the eye to focus is

different with different animals. It is the best developed in man and in apes.

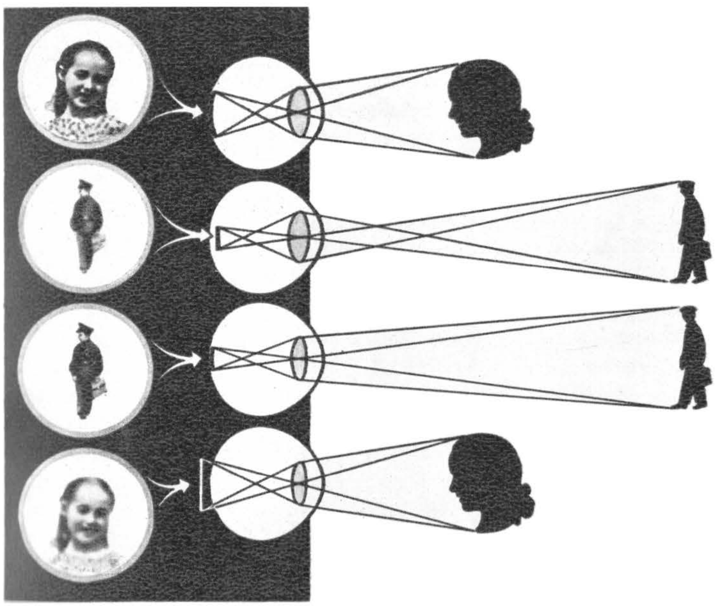
Incidentally, until recently, it was not known to engineering how to focus various photographic and cinema apparatuses automatically. At present the very first steps are being made in this direction, and it appears that automatic focussing is anything but a simple problem.

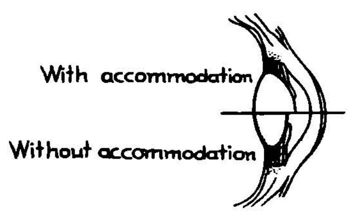
The ability of the eye to produce a sharp image of objects at different distances is called accommodation. Accommodation or focussing is achieved by means of the crystalline lens. But it does not involve longitudinal movement of the lens in the eye along the optical axis; it is accomplished by changing the curvature of its surface or, in other words, by changing the focal length of the eye's optical system. When we look into the distance, the lens becomes the least convex and the focal distance the greatest; when we look at near objects the lens becomes more convex.

At one time the crystalline lens served as the model for the first glass lenses. Many centuries have passed since then and the art of founding and working glass has reached a high degree of perfection. Optical factories of many developed countries prepare lenses of all kinds of shapes and sizes from optical glass. Some can be seen only with a magnifying glass, others are huge in size. For instance a glass mirror made for the reflecting telescope of the Crimean Observatory weighs 4 tons and has a diameter of 2.6 metres. It took 15 months to grind it, and this had to be done at strictly constant temperature.

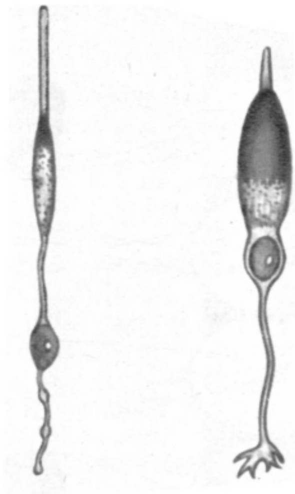
Very recently scientists and engineers succeeded in creating new types of lenses with very valuable properties. These are known as transfocal lenses, the focal length of which can be varied over a wide range at the operator's will. They are very complicated optico-mechanical systems consisting of several glass lenses, each with an invariable focal length.

But so far nobody has succeeded in inventing a one-piece lens with a variable focal length. It is impossible to make a lens after the type of the crystalline lens of the eye, using unelastic glass. New optical materials will be needed for this purpose. Now, when the plastics industry is develop-





The variable convexity of the crystalline lens enables distinct vision of objects and people at various distances. On correct accommodation the image is focussed exactly on the retina and is perceived sharply. The eye of a short-sighted person focusses the image not on the retina, but closer to the lens; that of a long-sighted person focusses the image beyond the retina, outside the eye. To see distinctly, short- or long-sighted people should wear spectacles.



A rod (left) and a cone.

ing so rapidly, it may be hoped that a plastic will be found that is suitable for making an artificial crystalline lens. It is needed very badly in medicine for curing a formidable disease—cataract, or turbidity of the lens. But not only the sick need it. It may safely be stated that the invention of a lens with a variable focal distance would cause a revolution in a number of branches of the optical industry.

The chorioid mentioned above is not the last layer. It is followed by a coat of specific cells containing fuchsin, or black pigment. Their purpose will become clear a little further on.

Finally, the most important and most interesting layer is the retina. The retina is what enables our eye to see. It is very complex in structure, consisting itself of many layers. There is no need to go into all of them here, the more so that the functions of some of them are still not clear to science. But we shall dwell in detail on the cells that take in the light and convert it into signals to the brain. These cells have been studied rather thoroughly.

It appears that there are two types of light-sensitive

cells in the retina. These are rods and cones, so named for their shape. If you look at their image, however, you will see that the resemblance to actual rods and cones is very distant. This is another example of how important it is to select scientific terms carefully and how cautious one must be in interpreting even simple words if they are used simultaneously in scientific language.

The inside of the eye between the crystalline lens and the retina is filled with a specific transparent substance called the vitreous humour.

The light-sensitive cells are very small. The diameter of a rod is about 0.002 millimetre (2 microns) and its length is about 0.06 millimetre (60 microns). The cones are a little larger (0.005 millimetre or 5 microns, on the average, in diameter, and 0.07 millimetre or 70 microns long).

In the course of the evolutionary development of the eye, which appeared originally in the live creatures inhabiting the ocean, the first light-sensitive cells were the rods. They enabled the sea animals to see in deep waters, where there is only diffuse sunlight which has passed through a thick layer of water. Cones appeared much later, only after live creatures began to adapt themselves to life on dry land.

Rods contain a special purple-red substance called visual purple or rhodopsin. Under the action of light visual purple decomposes and is decolourized. The more light incident on the rod, the faster this process is accomplished. But when the light stops acting, the rhodopsin recovers its initial properties. The decomposition of rhodopsin is a complex photochemical reaction, the essentials of which are as yet not quite clear to scientists. But that is immaterial here. It is important only that this reaction is accompanied by the appearance of electrochemical potentials in the rod or cone, which are conveyed to the brain by the optical nerve. It is these electrical signals that bring information concerning the luminance, colour and shape of objects to the brain. In the latter they are decoded by special organs and are perceived as the image of the world around us.

Recently (in 1940) a violet-coloured light-sensitive substance called iodopsin was discovered in the cones. Its pur-

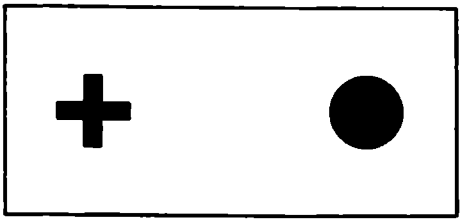
pose is the same as that of visual purple. But the role of the cones differs from that of the rods.

Rods are much more sensitive than cones. The rods enable us to see in twilight when the illumination is weak, but they cannot sense or distinguish colours. The saying "all cats are grey in the dark" is no joke. In the dark we really cannot discriminate colours, but can only sense different degrees of luminance: a road is lighter than the shrubbery growing along its sides, a distant forest is darker than the sky, but we can distinguish neither the green of the leaves, nor the blue of the sky, nor the colour of the road dust. However, no sooner does day dawn than everything changes around us, the whole world becomes bright and colourful; instead of vague hazy outlines we see everything around us in a splendid variety of hues. We owe this to the cones: it is they that make colour vision possible for us.

The number of rods in the human eye is very large—about 130 million, approximately one and a half times less than the population of the U.S.S.R; the number of cones is much smaller—7 million, or about the same as the population of Moscow. The rods are arranged all over the surface of the retina, while the cones are grouped in its central part, especially in its "capital" called the yellow spot.

Of course, this comparison must not be taken literally. There are cones in the other parts of the retina as well, and there are rods in the yellow spot. But in the yellow spot cones predominate, whereas in the rest of the retina the rods are in the majority. Nevertheless, it was not without reason that we compared the yellow spot to a capital. It is really a very important area of the retina. Because only those objects which are projected on the yellow spot are visible in detail; and we see especially distinctly those whose images fall on the central part of the yellow spot, where the central depression is situated. The surface of the central depression contains only cones (from 30 thousand to 50 thousand). As to the parts of the image that fall on the rest of the retina, outside of the yellow spot and especially the central depression, they are much less distinctly visible.

The rods and cones are connected to the fibres of the optical nerves, by which the signals produced by the rods



Close your left eye and keeping your right eye on the cross, move the book nearer and farther until the dot disappears. This means that the image of the dot has fallen on the blind spot.

and cones are transmitted to the brain. There are 137 million light-sensitive cells in the eye, but only one million fibres in the optical nerve. Hence it may be assumed that a nerve-ending may be "hooked up" to several cells. This assumption is correct. In the peripheral parts of the retina each nerve-ending is connected to many (from 100 to 400) rods and to several cones situated in the same area. But in the central depression each cone is connected to a separate nerve fibre.

All the nerve fibres converge in the eye at one point and here they form a million-conductor "cable"—the trunk of the optical nerve—which is "hooked up" to the brain. The point of the retina where the nerve fibres collect into a single cluster and from which the trunk of the optical nerve takes its origin, contains no light-sensitive cells. This is the blind spot of the retina. We cannot perceive images which fall on it. The blind spot is fairly large, practically no smaller than the yellow spot. Its area could accommodate the image of 11 full moons or a five-storey building several hundred metres away.

It is interesting to note that we hardly ever sense the presence of such a large blind area in our eye. Only sometimes when we are looking at the sky we suddenly see a rapidly moving black point. This is not an aeroplane, nor a bird, nor any other far-off object, because no matter how we try to concentrate on the point, it immediately escapes us which is not characteristic of any outside object.

The reader can convince himself of the existence of the blind spot by looking at the cross and black dot in the figure. Close your left eye and look intently at the cross. Then move the book page with the figure away gradually to a distance of 20 or 30 centimetres. There will come a moment when you cease to see the dot, because its image at that moment will be in the area of the blind spot. You will have to exert some will power and practice a while before you get results.

Why it is difficult to perform this experiment and why we do not notice the hindering action of the blind spot, we shall find out a little later.

Not infrequently one hears it said that many animals (say, dogs or cattle) cannot distinguish colours, that the world looks colourless to them, as it does to us in black-and-white moving pictures. This is not true. Cones are not the sole privilege of man. All animals which have cones in their eyes can distinguish colours.

Moreover, diurnal animals contain almost exclusively cones in their retina. Such is the case with many birds, including chickens and pigeons. Birds' retinas have more than one yellow spot: two or even three. Not long ago scientists made experiments and found that the pigeon distinguishes colours even better than man.

It is a well-known fact that chickens "go to bed" very early. If they are awakened at night, their behaviour is very fussy and foolish. Often during night fires they even rush into the fire. Now we can easily account for their going to sleep early and even their unnatural attraction towards a night fire. This is due to the fact that their eyes contain almost only cones, and therefore they grow blind as soon as twilight falls. And if a frightened hen is taken from its roost at night, it will be absolutely blind; the only thing it can see is the fire and the most brightly illuminated spots. It is quite clear that it will rush to where its blindness is likely to be lifted and it will not feel so helpless, where the main sense organ that has hitherto saved it from all dangers will be able to function.

On the other hand, the eyes of owls and bats, which have to be able to see well in the dark, hardly contain any cones and they are all very bad at distinguishing colours.

True, the bat does not rely much on its eyes at all, and therefore its ears often serve it instead of eyes. While flying the bat emits a very loud abrupt squeak. We cannot hear it because it is a very high-pitched ultrasonic squeak, but the bat itself hears its echo as it is reflected from obstacles of any kind (even a hanging wire) and can guide its flight excellently by it.

Properties of the Human Eye

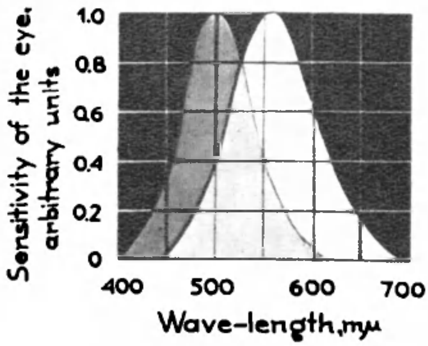
Oh, wond'rous wonder!

The properties of the eye are so astonishing that they are fit to be sung by the poets. It is difficult to say how this could be done, because to give a good idea of the properties of the eye one has to state the figures characterizing them. But this is one of the rare cases where figures are truly poetic.

The human eye reacts to light radiations in the range of wave-lengths from 380 to 770 millimicrons. As is evident from these figures, the shortest visible wave-length is only twice as small as the longest. To draw an analogy with sound, it may be said that the range of perceptibility of light waves constitutes only one octave (the range of perceptible sounds is about ten octaves).

At the ends of the range the sensitivity of the eye equals zero and increases smoothly inwards, approximately to its middle. In the daytime the maximum sensitivity is at a wave-length of 555 millimicrons (nanometres). And that is why we see rays of yellow-green light best in the daytime. The maximum of solar radiation is approximately at the same wave-length. Rays of this wave-length are reflected the strongest by the green leaves of plants and by grass, which gives them their yellow-green hue. It may be supposed that such a coincidence is not accidental, and that the eye acquired its maximum sensitivity at a wave-length of 555 millimicrons in the course of evolutionary development.

In the evening, when twilight falls, the cones are shut off and the process of vision takes a somewhat different course. The maximum sensitivity of the eye shifts towards the region of blue rays, to the wave-length of 507 milli-



Sensitivity of the human eye. In the daytime the eye is the most sensitive to yellow-green light rays. In twilight, when most of the work is done by the rods, it is the most sensitive to blue rays.

microns. That is why in twilight everything around us seems bluish.

Now it will be interesting to tell about the range of illuminations in which the eye can function normally. It appears that this range is very wide. We can perceive light even when only a few dozen photons fall on the retina. If it were absolutely dark on the Earth's surface at night, in clear dry weather we could see a burning stearin candle 30 kilometres away!

However, it is never completely dark on the Earth's surface. Even on a moonless night, the stars (visible and invisible), the light scattered by the atmosphere and the luminosity of the atmosphere itself, the reflection of the Aurora Borealis and zodiacal light together give an illumination of not less than 0.0003 lux. That is the illumination of a candle at a distance of about 60 metres. Still, under conditions when we can refill a film cartridge without resorting to a cover of any kind, our eye can function. We are still able to distinguish large objects and move around without bumping into them.

But on a sunny day, when the sun is close to the zenith, even in our latitudes the illumination reaches several tens of thousands of lux: 50 thousand lux is not the limit by

far. This is the illumination caused by a lamp of 50 thousand candle-power at a distance of 1 metre. But even with such bright light the human eye continues to work well: we see all our surroundings very distinctly.

To get a better idea of the range of illuminations we have to deal with, have a look at the following table.

Sun	100 thousand lux	
Full moon, clear sky	0.2 lux	Illumination from a candle at 2.2 metres
Venus, at maximum phase	1.1×10^{-4} lux	Ditto, at 100 metres
Syrius	9×10^{-6} lux	Ditto, at 300 to 330 metres
Star of first magnitude*	8×10^{-7} lux	Ditto, at 1,100 metres
Star of sixth magnitude (visibility limit for naked eye)	8×10^{-9} lux	Ditto, at 11 kilometres
Star of 24th magnitude (detectability limit in photographing with most powerful telescope)**	5×10^{-16} lux	Ditto, at 44 thousand kilometres

Scientists have established the maximum and minimum illuminations at which the eye is just not blinded. The ratio of these limits (the upper to the lower) is the fantastically large number 10^{12}, or a million of millions. No instrument has yet been invented which could function over such a wide range without special supplementary devices. True, the eye also possesses special devices which help it to adjust itself to work under such different conditions. Such adjustment is called adaptation of the eye.

Several processes take place in the eye during adaptation. One of them, namely, the change in diameter of the pupil,

* The concept of stellar magnitude formed historically. It has nothing to do with the actual size of the luminary, and characterizes only its visible, not absolute, brightness. A star of the first magnitude gives an illumination of 8.3×10^{-7} lux on the pupil of the eye. A star of the second magnitude gives an illumination 2.5 times less than that of a first-magnitude star. One of the third magnitude, 2.5 times less than that of a second-magnitude star, etc.

** This limit is not fixed. It changes with the progress of technique.

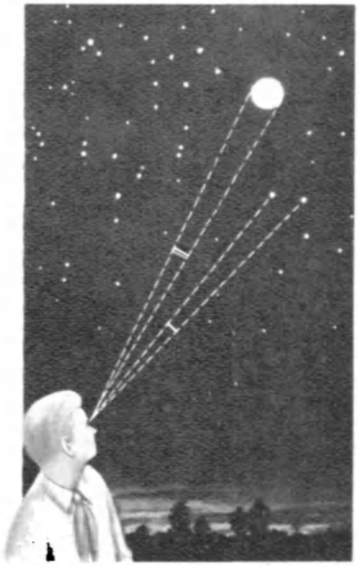
we already know. Another process is carried out by the cells containing the black pigment. Under the action of bright light this pigment, often called fuchsin, is evolved by the cells and penetrates into the layers of the retina. Here it coats the light-sensitive cells, reducing the access of light to them. At low illumination the fuchsin leaves the retina, making it more accessible to light. There is no difficulty in guessing what the third process must be. It relates to the different sensitivity of the cells—the rods and the cones. In bright light both the rods and the cones function. In twilight, however, the luminous energy is too low for decomposition of the rhodopsin in the cones to occur, and they are completely "shut out". But the rhodopsin contained in the rods decomposes even under the action of very small quantities of light, and signals from the rods continue to be transmitted to the brain via the nerve fibres.

Adaptation of the eye does not occur instantaneously. A certain amount of time must pass before the eye gets used to the new conditions. When we come out of the dark into bright light, we blink at the light and even sense a painful irritation of the eyes. Fortunately, our eye adapts itself completely to new conditions in 30 to 40 seconds. If the situation is reversed (on passing from bright light into the dark) adaptation takes much longer. Colour vision adapts itself in 5 to 8 minutes, while the rods acquire the necessary sensitivity only in 30 to 80 minutes.

Another very important property of human vision is its acuity, that is, the capacity for seeing separately two objects situated very close to each other.

You can check the acuity of your vision quite simply. All you have to do is to try to distinguish closely located stars in certain constellations on a clear (better, moonless) night.

The easiest to find are Mizar and Alcor in the constellation Ursa Major (the Great Dipper). The angular distance between them is rather large—it equals 12′, and a person with normal eyesight can readily see a small star next to the second star in the handle of the dipper. Those who are better acquainted with the star map can check their eyesight further by the stars. Thus, there is a double star in the constellation Goat, called alpha-Goat (α Goat). Here

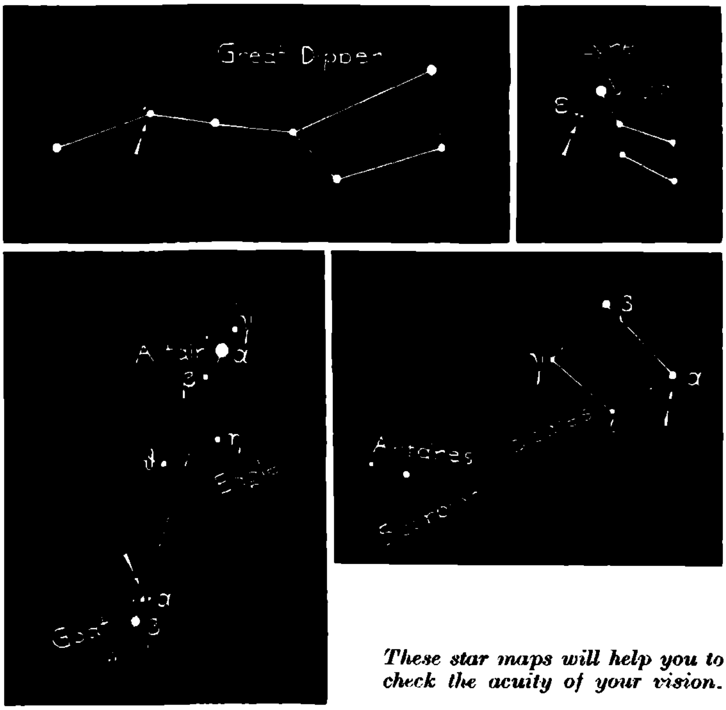


The angular size of a body is the angle between the rays running from two opposite edges of the body to the observer's eye. The angular distance between two objects is the angle between the rays running from the centres of the objects in question to the observer's eye.

two stars can be discerned of the 3.5 and 4.5 magnitudes. The angular distance between them is 6′. Similarly, alpha Scales (α Scales) consists of stars of the 2.8 and 5.3 magnitudes; they are separated by an angle of 4′. Still closer stars are to be found in the constellation Lyre. Their magnitudes are 5.3 and 6.3 (that is, in brightness they are on the threshold of visibility), and the angular distance between them is 3′. Anybody who can resolve epsilon Lyre (ε Lyre) into two stars has exceptionally, one might say, phenomenally good eyesight.

In his book "The Nature of Light and Colour in the Open Air" Professor Minnaert writes:

"Exceptionally good observers, of which there are very few, can distinguish an incredible amount of detail when



These star maps will help you to check the acuity of your vision.

the sky is bright and the atmosphere calm. One of them asserts that with the naked eye he can see α of the Scales as a twin star.... Saturn is, to him, distinctly oblong, and Venus crescent-shaped, at favourable moments, if he looks at it through a smoked glass or through a cloud of smoke that happens to be of the right transparency. He is even able to see two of the satellites of Jupiter, though only in the dusk, when the stars of the first and second magnitudes are beginning to appear."

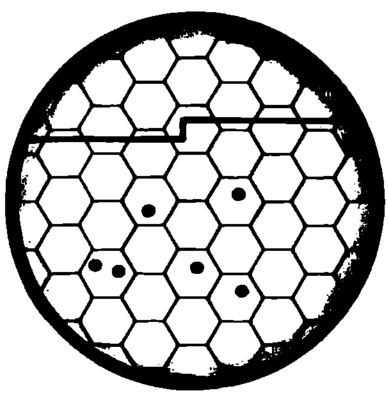
Most of us can only envy such excellent, veritably eagle eyesight. It enables one to see numerous interesting things that are usually hidden from us. Although not all of us are lucky enough to have such good eyesight, anyone can increase the acuity of his vision. To do this we must train our eyes, develop our power of observation. Only

great care must be exercised not to overfatigue the eyes when we are doing it.

Acuity of vision was investigated by scientists in the laboratory as well. It was found to be very high even for an ordinary observer. We can distinguish two objects even if they are separated by angular distances of about 1′. But this is not the limit. Some observers can distinguish intervals down to 10″. To get a better idea of these values it should be remembered that the angular size of a man about 6.5 kilometres away from the observer is equal to 1′.

Objects whose images fall on the central depression can be seen the most distinctly. The acuity of vision values given above refer to observation of the object with the aid of this depression. You have probably already guessed why vision with the central depression is the most acute. In this area each light-sensitive cell is connected to a separate nerve fibre and, therefore, separate signals come to the brain from each cell.

It is thought that two objects can be seen separately if their projections on the retina are so situated that there is

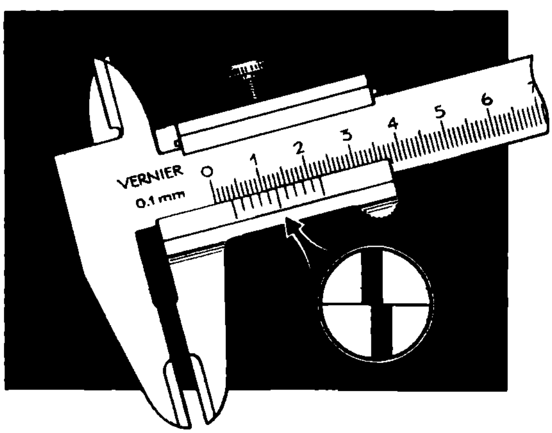


Here you see the arrangement of the images of small objects on the retina of the eye. If the objects are projected on to the same light-sensitive cell or on to two adjacent ones, they cannot be perceived separately. If the images of the objects are separated by at least one unoccupied cell, they are perceived separately. Breaks in lines are perceived even if they are as shown in the figure.

at least one "unoccupied" light-sensitive cell between them. This assumption is evidently not far from actuality: an object with an angular size of 1′ produces an image on the retina about 0.004 millimetre in size, which is close to the average diameter of a light-sensitive cell.

But, on the other hand, some people are known to have much more acute vision. How can this be accounted for? Among other reasons, scientists point out that highly acute eyesight is possessed by people whose light-sensitive cells are much smaller than the average. Very acute vision is especially common in people inhabiting prairies and deserts or in seamen. Such, for instance, are the inhabitants of the Kirghizian Steppes, such are the Patagonians of South America.

This assumption is borne out by the results of investigating the size of the light-sensitive cells in birds' eyes. It was found their size is different for different species. Those that do not require very acute vision have rather large cells. But eagles' eyes have cones as small as 0.0003 to 0.0004 millimetre in diameter, that is, about 10 or 15 times as small as those of a man with average eyesight.



The ability of the eye to discriminate breaks in a straight line makes it comparatively easy to design the scales of various instruments and measuring devices. The design of verniers, say, on vernier calipers is based on this property of the eye.

Up till now we have been speaking of distinguishing objects separated by a small interval. Another property of the eye is its ability to discriminate even very minute breaks at the junction of two straight lines. Its sensitivity to such breaks is extraordinarily high: it is 10 and even 20 times higher than its sensitivity to the discrimination of separate objects. Although science has not accounted for this fact as yet, it has long been taken advantage of in practice; many very precise measuring instruments are designed to make use of this feature of vision. Such, for instance, are all vernier devices, all scales of indicator-type measuring instruments.

Is the acuity of vision always the same? Of course not. Our eye sees distinctly only in bright light, in the daytime. In twilight and especially at night the acuity of vision becomes much lower. Besides, in the dark even a person with very good eyesight develops nocturnal shortsightedness: distant objects become indistinct and hazy. This fact should especially be remembered by those who like to read in twilight without putting on the light. Such reading tires the eyes very quickly and if done often may spoil them.

Now that we know about the structure of the eye and the acuity of vision, it is necessary to say a few words about the field of view. The field of view is the entire space in which objects can be discriminated by the eye at rest. The scope of the field of view is usually expressed in angular units. Its boundaries differ slightly for different persons and depend, besides, on the size and even the colour of the objects viewed. For white light the boundaries of the field of view are as follows: 70° downwards, 60° upwards, 60° inwards (towards the nose) and 100° outwards (towards the temple). Within this field is the blind spot with an angular size of about 7°, the yellow spot of about the same size and the central depression whose angular size is 1 to 1.5°.

We see the most distinctly with the aid of the central depression.* Here the acuity of vision is the greatest. But

* In twilight, when only the rods are functioning, the maximum acuity of vision is not in the central depression, but outside of it, even beyond the yellow spot.

Field of view of a stationary eye. The eye sees distinctly only in a very small zone (circle in centre); in the rest of the field of view the image is perceived much less distinctly.

at 3 to 5° from it the acuity of vision is already almost 4 times worse, and near the boundaries of the field of view it is very low, about 30 times worse than in the region of the central depression and even the yellow spot.

The attentive reader will certainly be surprised at such figures. Indeed, what does man need such a wide field of view for, if he can see distinctly only within so small an angle as 1.5°? Moreover, he might question the correctness of the latter figure: is it not too small? It contradicts our everyday experience, which tells us that we see everything around us almost equally distinctly.

Science is now in a position to answer these questions, though not quite completely. An exhaustive explanation will become possible only after all the processes occurring not only in the eye, but in the vision centres of the brain have been studied. In our times scientists have just started

in on this problem. It is so complicated and many-sided, that its solution will require the combined efforts of physiologists, biophysicists, biochemists, electronics experts, and many others. Even with modern possibilities and the headlong march of science, it will probably take many years to study and solve this problem.

Now what do we need such a wide field of indistinct vision for? A very interesting property of the eye makes it possible to answer this question. It appears that the peripheral part of the retina, which can usually discern only large objects, is extraordinarily sensitive to the movement of small objects. Thus, if a small stationary object is projected on to the periphery of the retina, we are not able to notice it. But no sooner does it begin to move, than signals begin to flow to the brain. On the basis of these signals we cannot judge the shape of the object, but they are sufficient to determine the whereabouts of the object and the direction of its movement. If for some reason or other the object attracts our attention (expectation, danger, etc.), we practically instantaneously and most often automatically shift our gaze to it, or, in other words, turn our eyes so that the image of the object should fall on the area of distinct vision. This property of peripheral or side vision is very important. It helped our forefathers to track their prey and to escape being taken by surprise.

Peripheral vision is necessary to man now too. Though not distinct, it is sufficiently good to give us an idea of the surroundings (it is still many times better than the vision of insects, particularly, dragon flies). Owing to it, we can find our bearings quickly and correctly and choose the direction of our movements. It is vitally necessary to flyers and car drivers; without it neither work nor sports could exist.

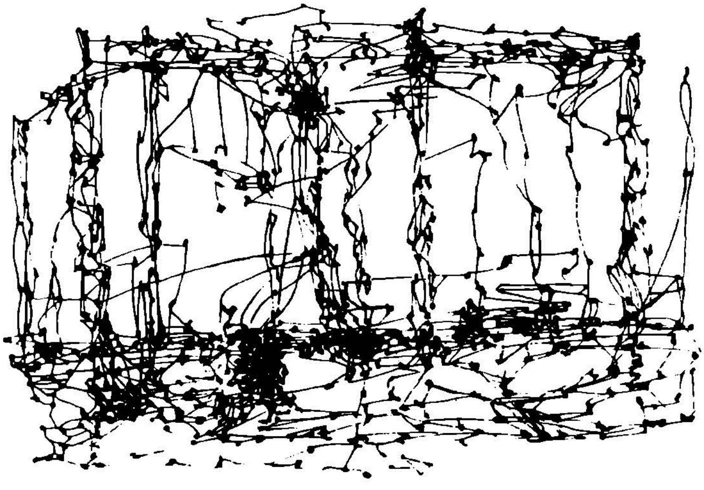
But would it be worse if our eyes were so designed that they could see equally distinctly over the whole field of view? Before answering this question we must remind the reader that in the region of most distinct vision there is a separate optical nerve fibre for each of the 50 thousand light-sensitive cells. It is due to this elaborate connection between the cells and the brain that vision with the help of the central depression is so acute. To make vision just

as acute on the peripheral part of the retina, a separate nerve fibre would have to be connected to each light-sensitive cell in this area too. Then the optical nerve trunk would have to accommodate 137 million fibres instead of a million, it would have to be 10 or 12 times as thick as it is, and would resemble a fairly heavy rope. But this is not the main thing. It is far more important that the vision centres of the brain would occupy an unjustifiably large space. They would have to develop at the expense of some other important cerebral centres or by increasing the total volume of the cerebrum. Both ways are impossible and unnecessary. Nature—the greatest of inventors!—found a more correct and economical way. She granted man the possibility of seeing very distinctly, but only as far as necessary, in a comparatively narrow solid angle of a size that is actually indispensable in life. And in order that man should be able to take his bearings quickly and efficiently and to evade danger, she provided him with side vision and the ability to notice small (to say nothing of large) moving objects even when they are beyond the field of distinct vision.

But besides this, vision has one more remarkable property. It is this property that makes it possible to see very distinctly over a wide field of view with the aid of a very small central depression and a slightly larger yellow spot. Owing to this peculiarity we seem to perceive everything around us simultaneously, at once and equally distinctly. Suppose we are in one of the halls of the Tretyakov Art Gallery. Say, in the one containing the canvasses of the famous landscape painter Shishkin. Let us stop before one of them, for instance, that entitled "In Mordvinova's Wood". This picture, rather study, was painted by the artist from nature near Oranienbaum. It depicts a dense and gloomy fir wood, a glade in the foreground, moss-covered mounds overgrown with saplings; and a little farther back, slightly to the left of the centre, an old man leaning on a stick. We see the whole picture equally distinctly in all its parts. Moreover, we are certain we see all of it at once and simultaneously.

Actually, this is not so. In reality, at each separate moment we perceive only one comparatively small area of

Photograph of Shishkin's "In Mordvinova's Wood" and "photograph" of the movements of the eye of a person looking at the picture.



the picture. This is because our eyes do not stay at rest when we are looking at anything. They keep moving incessantly, "running over" the object observed. The brain, however, gets an integral image, because it remembers each of the consecutively viewed areas and pieces them together like toy cubes to make a single image. We can convince ourselves of this by looking at the illustration. Above is a photograph of Shishkin's "In Mordvinova's Wood", while below.... Below is also a photograph. If we look intently and attentively at the lines and points, we may notice that all together they make up something resembling Shishkin's canvass. What kind of photograph is it? It is a photograph recording the movements of the eye of a person viewing the picture.

It was obtained in a very ingenious way by the Soviet scientist A. Yarbus. A very small light mirror was fastened to one of the eyes of the observer and a ray of light was directed at it. The beam reflected by the mirror fell on a piece of sensitized paper and left traces on it. When the eyes turned (in man, both eyes turn identically) the beam moved over the sensitized paper following exactly all the movements of the eye looking at the picture.

After the experiment the paper was developed. And the result was a "copy" of Shishkin's picture, drawn by the eye. The bold points on the copy correspond to the moments of time when the eyes remained stationary, while the thin lines joining the points record the quick jerky movements of the eyes as they changed their direction.

Scientists have established that vision always occurs broadly speaking in the following way: the eyes stop motionless for a short time, then take a quick small "hop", stop again and then hop again. This is just how we always view our surroundings or follow any single object with our eyes. The eye makes up to 120 hops and stops per second. Each hop is not more than 0.5° and its duration is about thirty times less than the time the eye remains at rest and directed at one of the parts of the object. The time the eye remains stationary is between 0.2 and 0.8 second. During this fraction of a second the eye is able to look over and the brain to remember what is seen. If the area viewed is not too large we perceive it as an integral whole

and do not notice that in reality we are seeing it by parts.

Such a hop-wise process of viewing space (scanning of space, as it is called in engineering) is of fundamental importance. Without it vision would be altogether impossible. By means of special experiments scientists have established that if an unchanging image is projected on the same area of the retina, it will remain visible for only a few seconds. After this the area becomes saturated, as it were; it stops seeing the image and becomes blind. Such experiments show clearly that the eye can observe well only objects whose image moves over the retina either owing to the movement of the object itself, or as a result of the hop-wise change of the direction of view.

Knowing how space is viewed, it is easy to explain why we do not notice the blind spot. This is because our glance never remains fixed for any length of time at the same place. If the eyes were immobile, the blind spot would also be immobile and the same part of the image would always be projected on it. Actually, however, the blind spot alternately "covers" different areas. The areas alternate often enough to keep the brain from forgetting them before necessary. The difficulty in carrying out the experiment with the cross and the dot is also due to this hop-like process of vision during which the eyes do not remain at rest.

There is another very important property of vision worth mentioning, that, in a certain sense, should possibly be classed among its shortcomings. However, scientists and engineers have carried out thorough investigations and have succeeded in making such brilliant use of this shortcoming, that it has become a very important advantage Without it cinema, television, and a number of other important fields involving the joint use of light and the eye would be inconceivable. What is meant is the inertia of visual perception, that is, the fact that we do not see an image instantly, but only some time after it has appeared, and continue to see it after it has disappeared.

Owing to the inertia of vision, we cannot discriminate quickly moving parts of a machine, the spokes in the wheel of a moving bicycle, the arms of a revolving propeller, a cannon shell in its flight, the movements of a bee's wings,

and many other things. But only thanks to this property are we able to see at all in dim light because the inertia of vision is directly related to the ability of the light-sensitive cells to accumulate the action of quanta. If the number of photons incident on a light-sensitive cell per unit time is greater than a certain minimal value known as the threshold of sensitivity of the eye, their action can accumulate or, in other words, add up in time owing to the inertness of vision.

The sensation of vision arises as a result of the decomposition of a light-sensitive substance in the rods and cones when light falls on them. After the light stops, the reverse process begins, and the light-sensitive substance is restored. The more intense the light falling on the eye, the faster its decomposition. But it is restored the faster, the deeper the darkness after the light has disappeared.

The sensation of light usually appears after 0.05 to 0.2 second, depending on the intensity of the light. Disappearance of the light sensation takes longer, is more gradual.

At present, so-called fluorescent lamps are often used for lighting, and gas-discharge lamps for advertisements. Both of these possess a property which distinguishes them radically from ordinary incandescent electric lamps. This property consists in the fact that when connected to a source of alternating current (which is now employed almost everywhere) these lamps emit continuously pulsating light.

The frequency of the alternating current used in the U.S.S.R. and in all European countries is 50 cycles per second. This means that in the course of a second the voltage changes its polarity 100 times: it is maximal in magnitude and positive in sign 50 times, and maximal and negative the same number of times. In between the maxima the voltage diminishes smoothly to zero and equals zero 100 times each second. The brilliance of the light keeps time with the voltage: there are 100 flashes per second, and their brilliance grows, reaches a maximum and drops back to zero.

If our eyesight did not possess inertia, everything in the light of a gas-discharge lamp would be now brightly illuminated, now plunged in darkness, as if lit up by very frequent

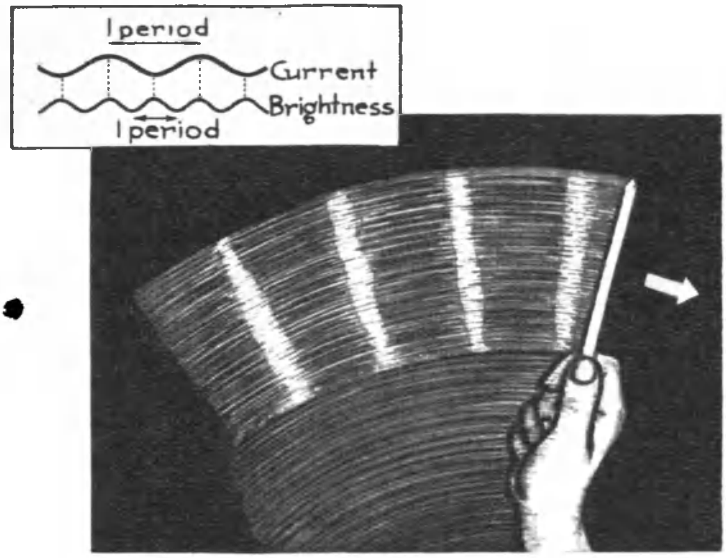
flashes of lightning. However, this does not happen, because the light-sensitive substance in the rods and cones can neither decompose nor be restored instantaneously, but requires a tangible length of time for this. That is why we hardly notice the glimmering of fluorescent, mercury and gas-discharge lamps.

Hardly.... But not altogether, even when the light is pulsating 100 times per second. Such pulsations are very easy to detect if we take the trouble to do so. All we have to do is wave our hand with the fingers spread out, or better, a shiny thin rod, through the air, and we shall observe an unusual phenomenon: instead of the continuous translucent band obtained in the daytime in such a case, the eye sees a large number of separate slightly hazy bands.

Cut out the black-and-white disk given in the appendix and try the experiment indicated in the light of such lamps. Try to explain why, when the disk is revolving at a certain speed, the rings on it seem to rotate in opposite directions. Explain why this is not observed in daylight and why the effect is very feeble in the light of incandescent lamps.

And now another experiment. Look at a match flame or a burning incandescent lamp (only take care that it is not too bright), and then quickly transfer your glance to a piece of black velvet or black paper prepared beforehand. If neither is available, you may transfer your glance to a dark corner of the room instead. When you do this you will find that the image of the flame or of the white-hot filament remains, though dimmer, for some time after you have stopped looking at the luminous object. In this case you see its after image, or rather, its positive after image.

The origin and existence of after images depends on the fact that the process of restoration of the light-sensitive substance in the rods and cones requires a certain length of time. Now, repeat the above experiment, but this time continue it further. When the after image of the bright object grows dim, quickly transfer your glance from the dark ground to a uniformly and brightly illuminated sheet of white paper. On it you again see the previous image, though still hazier and dimmer than before. But the important thing is that the image is now dark on a light background. This is also an after image, but now it is a negative one.



Moving thin shiny rod in the scintillating light of a fluorescent lamp. Top, left, curves showing the variation of the current flowing through the lamp and the variation of the brightness.

The appearance of negative after images is due to the fact that the areas of the retina which have been exposed to bright light become less sensitive than those on which no rays of bright light have fallen. This non-uniform distribution of sensitivity remains imprinted on the retina for several seconds. If we look at a uniformly illuminated white sheet during this period, it will be perceived as a darkened area on the white surface, corresponding in shape to the object we had been looking at before.

A few words about the peculiarities of binocular ("two-eyed") vision.

Until now in talking of vision we did not distinguish between the cases where the object is regarded with one or with both eyes. Indeed this was unnecessary until we came to the question of the sensation of depth, of the ability to estimate distance to objects in our field of view.

An ordinary snapshot or picture gives the viewer a sense of depth. However, this sensation does not change whether we look at the image with one or with both eyes.* In this case the sensation of depth is caused by the linear and aerial perspectives. The former enables us to judge how close or distant the objects are by the size of their images. The latter supplements the former by the outlines and surfaces of the objects becoming less and less distinct, the farther they are away from the foreground. If the image is coloured besides, the colours of distant objects change too: they seem paler, as if dissolving in an airy haze.

We get the sensation of the depth of real space in a similar way when we are using one eye, and we do not feel much difference between vision with one and with both eyes. But this difference is great.

Try a very simple experiment. All you will need for it is two ordinary pen nibs, or if you use only a fountain pen, two matchsticks will do, though with them the experiment will be less effective. This experiment should be performed without previous practice.

Put the nib on a box or a book so that its point sticks out over the edge. Then take the second nib in your left hand. Close one eye and try to touch the point of one nib with the other, moving your hand smoothly and continuously starting from a distance of 20 or 30 centimetres. Now do the same with both eyes open. You will immediately perceive the immense difference between one-eyed (monocular) and two-eyed (binocular) vision. This experiment is even more convincing when observed from aside. Ask somebody to do it and watch the movement of the hand holding the nib.

By the way, just such simple experiments have helped scientists to get an insight into the innermost processes taking place in the organism, and to formulate certain important propositions of the new science of cybernetics.

The difference between vision with one and with both eyes can also be seen by looking at colour stereophoto-

* If we examine a high-quality snapshot with one eye at a definite distance the sensation of depth may be very strong: the photograph will seem to be stereoscopic.

graphs. Before you are two snapshots, or rather, one made with a stereoscopic camera. At first glance the left-hand and right-hand photographs are exactly the same. You can only see the difference between them if you superimpose one on the other. It is insignificant and is due to the fact that the left-hand photograph was taken at a slightly different angle of view than the right-hand one.

Try to look at both photographs simultaneously as indicated, though you will not find it easy to do so. After several trials, however, you may succeed in adapting yourself to it. Usually this happens unexpectedly and you suddenly notice that the space of the image acquires depth, and all the objects stand out as volume images.

Next you will see two more photographs. Do not think that these strange impressions making the image indecipherable are due to faulty printing. They were made on purpose. The red impression is the image for one eye and the blue-green one, for the other. Such stereophotographs are to be observed through special glasses. Cut out a pair of paper eye-glass rims and glue pieces of coloured cellophane (one red, the other blue-green) in each of the openings. Then look at the photograph through these glasses. You will again get an unexpected and delightful thrill from the depth and volume the image suddenly acquires.

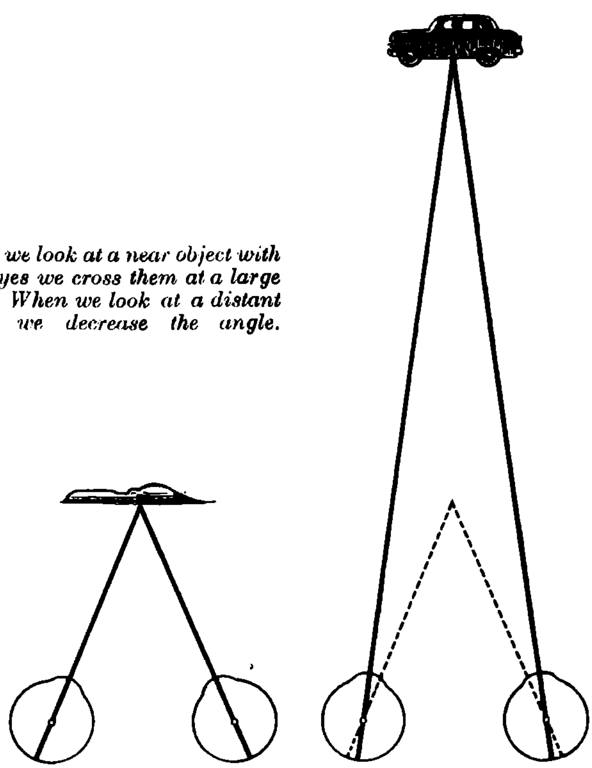
What is the reason for such a sharp difference between vision with one and with both eyes?

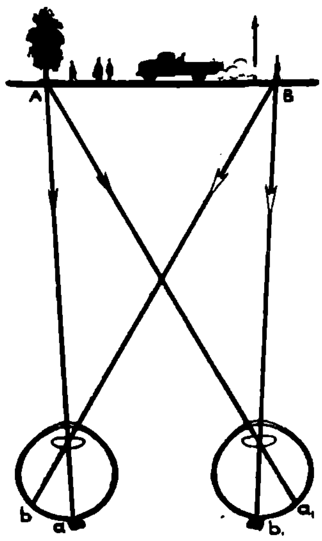
It turns out that this is primarily due to the structure and operation of the brain. The insignificant difference in the images for the left and for the right eye, a difference which we are not able to perceive when we look at each of the images separately, is taken into account by the brain when we look with both eyes and is transformed into a stereoscopic space image. Nobody knows yet how the brain accomplishes this. But it has been known for a fairly long time that a very important part in forming the sensation of depth is played by the muscles turning the eyes in their orbits and by the ciliary body controlling the accommodation of the crystalline lens in each eye. Signals depending on the tension of these muscles are sent to the brain by each eye. These are also taken into account by the brain and enable it to form a whole stereoscopic or three-dimension-

al image (that is, one having height, breadth and depth) from the two incoming two-dimensional images (the image on the retina of each of the eyes has only two dimensions—height and breadth).

Above we mentioned only one of the ways the deleterious influence of the blind spot is reduced. It was the hop-wise process of viewing space. Now we can point out a second way. It is comparatively simple. When we look at anything our eyes turn so that the object interesting us should be projected on to the region of the central depression and the yellow spot. This is natural—the line of vision passes exactly through the centre of the yellow spot, that is, the yellow spot is located symmetrically with respect to the

When we look at a near object with both eyes we cross them at a large angle. When we look at a distant object we decrease the angle.





The image of the tree falls on the blind spot of the left eye, and the image of the man on that of the right eye.

line of vision. As to the blind spot, it is located to the side of this line. In the left eye the blind spot is about 15° to the right of the line of vision (closer to the nose), in the right eye—just as much to the left of it (also closer to the nose). Therefore, the blind spot of the left eye covers a different area of the image than that of the right eye.

The images in the left and right eyes differ insignificantly, and the brain reproduces an integral image, inserting the corresponding part of the image obtained on the retina of the right eye over the part covered by the blind spot of the left, and similarly "patching up" the image of the right eye. The result is that the hindering action of the blind spots of both eyes becomes practically imperceptible.

Suppose we came across a poem that appealed to us so much that we decided to memorize it. We begin to read it over and over, trying to remember each word and the exact place it occupies among all the others. Some can do

this very quickly, others have to work hard for a fairly long time before the verses remain firmly seated in their memory. But sooner or later any psychically normal person will commit the poem to memory.

Now just what does this mean, to commit to memory? It means that even after many years the person will be able at will to repeat the poem word for word without cribs or prompting.

What is memory?

We know that a man's memory depends on how his brain works. But so far scientists cannot answer the numerous "how's" concerning the work of the brain. This is due to the fact that they still know too little about the activities of the brain owing to their inconceivable complexity.

Only the first steps have been made in this direction. And we still know too little about the most complicated, most perfect creation of nature—the human brain. And until we get to know the processes that take place in the brain in connection with remembering, we shall not be able to say exactly why verses are easy to memorize and prose difficult; why a melody is remembered easily, while the sounds of an orchestra tuning up, or any other noise, is not; why we easily remember geometrical figures, peoples' faces, pictures of great artists, but forget the canvasses of second-rate painters.

Only the first fruitful assumptions are beginning to be made about these processes, though nowadays they draw the attention of many scientists and engineers working in a great variety of fields of science and engineering. No doubt, in the near future considerable progress will be made in this direction, and maybe we shall witness the solution of the greatest mystery, the mystery of thought and memory.

Then we shall know for certain about one of the most interesting means of vision: about the ability to remember, distinguish and classify the infinite variety of shapes of the world around us. At present this property is called shape vision.

Here is what one of the founders of cybernetics, Norbert Wiener wrote about it:

"One of the most remarkable phenomena in vision is

probably our ability to recognize an outline drawing. Doubtlessly, the outline of the human face bears very little resemblance to the face itself with regard to colour and distribution of light and shade, and yet the portrait of a man is very easy to recognize in it."

The scientist got very interested in this ability, and here are the questions he asks himself and his readers:

"How do we recognize an individual human face when we see it in different positions: in profile, in three-quarters or full face? How do we recognize a circle as such, irrespective of whether it is large or small, near or far, in a plane perpendicular to the line drawn from the eye to its centre and looks like a circle, or otherwise oriented and looks like an ellipse?"

Then Wiener attempts to answer these questions and suggests one of the possible versions, one of the possible models of how the brain works to distinguish shapes. He does not insist that the brain actually works exactly that way, but the ideas he puts forth may be put at the basis of one of the hypotheses of the operation of the brain; besides, a mathematical machine can be constructed on the basis of these ideas, which is capable of distinguishing the shapes of objects, if only the simplest of them.

An interesting assertion was made by the famous architect of the Renaissance Leon Battista Alberti (1404–1472) who also dwells on the properties of shape vision in his treatise "On the Statue":

"Inasmuch as sculptors seek likeness, from likeness must we begin. Here I could take to reasoning on the nature of likeness, on why each individual greatly resembles all the other individuals of the same kind—we see this in nature, and see it observed in all living creatures. On the other hand, one cannot, so to say, find a voice quite the same as another voice, a nose quite the same as another nose, and, similarly, one cannot find a man among the entire multitude of people, who would be indistinguishable from others. Add to this that the faces of those we saw as boys and then knew as adolescents, and whom you knew as youths, are recognized even when they have become old men, no matter how great the changes their features have undergone with age from day to day. Thus, we may assert that there is

something in the very forms of the body that changes with time, and something else deep down and inherent in them that always remains stable and unchanged...."

It is evidently this stable and unchanged thing that shape vision notices, and that the memory retains for many, many years.

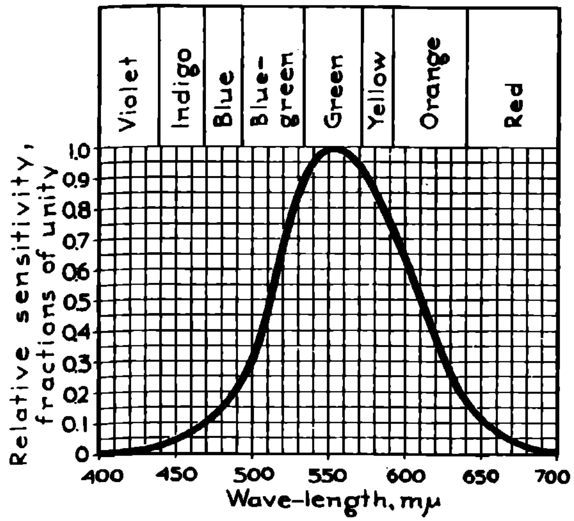
Colours

"...colour is the result of the action of a physical object on the retina."

V. I. LENIN.
"Materialism and Empiriocriticism."

Before discussing the nature of human colour vision, we must speak about the laws of formation of the colours.

In the spectrum of solar light consisting of an infinite multitude of pure colour hues passing gradually into one another, the human eye can distinguish more than 150 shades. Usually, the spectrum is divided into several colour groups: the group of violet hues, indigo, blue, blue-green, green, yellow, orange and red hues. In terms of wave-lengths, the boundaries between the corresponding groups are: 424, 459, 492, 532, 571, 596 and 645 millimicrons. The ends of the visible part of the spectrum correspond to the wave-lengths 380 and 770 millimicrons. It is interesting to note that, translated into the terms of the wave theory, the boundaries of the colour groups first outlined by Newton, hardly differ from those given above. Incidentally, Newton saw the analogy between the perception of colour hues and musical tones. We know that the same notes in two neighbouring octaves sound in harmony and differ only in pitch. The frequencies of such tones relate to each other as 1 : 2, and their wave-lengths, as 2 : 1. If we take the boundaries of the visible spectrum, their wave-lengths also relate to each other as 2 : 1. Now if we look carefully we can discern a likeness in colour between the ends of the spectrum—between the deep red and deep violet hues. "Colours," wrote Lomonosov, "are in surprising accord with music." No great importance is attached to this analogy in our times. But many cases are known in science



Sensitivity curve (visuality curve) of the human eye and boundaries between the corresponding groups of colours.

(and we are well acquainted with some of them) where ideas, which had been considered dead, came back to life.

The hues of the solar spectrum do not by far exhaust the entire variety of colours encountered in nature. There actually exist an infinite number of colours, and the number of them our eye can discriminate is difficult to count.

If we count up all the words meaning colours and their shades the number will be a fairly large one. That is why we have no difficulty in describing even very subtle differences in colour. Nevertheless, this description is insufficient when we need exact knowledge of a colour. Professionals, even house-painters and signpainters, to say nothing of artists, use other words. For instance, paints giving different shades of red have the following names: madder lake, brilliant lake, cinnabar red, cadmium red, carmine, minium, etc. These names indicate quite definite shades, because paints are made according to formulations and technologies

that remain unchanged from year to year and because the paint factory always has standard samples with which all new products are matched. Of great help in selecting colours accurately are colour books in which each sheet is of a strictly definite colour.

But at the modern stage of development of science and industry this is far from sufficient. Engineering generally prefers exact figures to words, the interpretation of which is always more or less indefinite. And so there arose and developed a special branch of optics called colorimetry, which has to do with exact method of determining colours and the laws of their formation. Colorimetry is also based on the exact knowledge of definite properties of human colour vision. It proceeds from the laws of formation of the colours in the human eye, established by numerous and repeatedly verified investigations.

However, there is no hurry to describe these laws. Let us continue our talk on colours first.

First of all, it should be pointed out that in colorimetry white, black and all the intermediate shades, absent from the spectrum, have equal rights with all the rest. True, they constitute a specific group of so-called achromatic colours (which means, literally, uncoloured colours). The entire gamut of greys can be obtained by mixing white and black in various proportions. In principle, this gamut contains an infinite number of colours, but our eye is able to discriminate about 300 gradations in it, which is not so few.

Any surface which reflects all the components of solar light equally (badly or well) has an achromatic colour. Under equal conditions of illumination the surface that reflects more rays seems lighter than one that reflects less. The whitest surface is one coated with magnesium oxide or barium oxide: it reflects up to 98 per cent of light incident on it. Pure white snow (sometimes even freshly fallen snow has a slight tint) seems grey on the background of such a surface, because it reflects only 85 per cent, while a white paint such as zinc white reflects still less—only 70 or 75 per cent. Surfaces coated with porous chimney soot seem very black, but black velvet is still blacker; some grades reflect not more than 0.3 per cent of incident light. The only

thing blacker than black velvet is a black body—a special device which we mentioned in the last chapter.*

All the colours except white, black and the greys constitute the group of chromatic (coloured) colours. It falls, in its turn, into two subgroups: the first includes the spectrally pure or monochromatic hues, the colour of which is determined by one wave-length only, and the second, the complex colours, composed of several monochromatic hues. The latter are in the majority. Rather, their number is infinite. No wonder artists say that no two colours in nature are ever exactly identical.

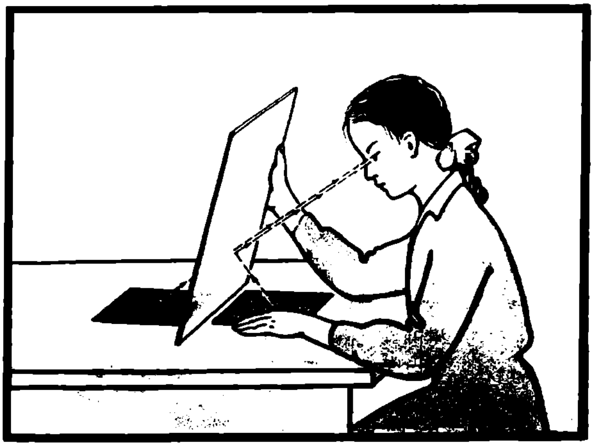
Scientists have established that all this diversity can be obtained by mixing the initial pure hues.

To get to understand this better, we can make a few very interesting experiments with a very simple apparatus. To make this apparatus take a small piece of glass, which must be washed clean and polished with tooth powder, and a piece of black velvet. If no velvet is available we may use a book in a dull black cover. Besides the glass and the velvet, we shall need pieces of white paper painted red, yellow-red, yellow, blue-green, blue and purple-blue with water colours. The colours should be applied as uniformly as possible in several layers, allowing the previous layer to dry before applying the next.

The apparatus is shown in the figure. Its action depends on the fact that the streams of light (and the images) from two areas of the surface are combined by means of the glass and sent together to the observer's eye. One of the areas of the surface is behind the glass; we see it because the glass is transparent. The second area is in front of the glass, and its image comes to the observer's eye after being reflected, as by a mirror, by the front surface of the glass. The latter usually does not reflect more than 10 per cent of the incident light. Therefore, the stream of reflected light will be much weaker than the stream coming from beyond the glass, but this can be corrected.

By means of this apparatus we can mix the light rays

* It must not be forgotten that a black body may not only absorb, but also radiate light. But in colorimetry it is assumed that bodies of black colour only absorb light



A very simple device for additive mixture of colours. Painted sheets of paper are placed before and behind the glass (it is best to put them on black velvet); the resulting colour can be seen in the glass.

of two different colours. The light sources will be the painted sheets of paper. We know that a blue sheet reflects blue rays, a yellow sheet—yellow rays and so on.

Arrange the sheets so that their images in the glass are imposed on one another. Then try tilting the glass towards yourself. In this way you will increase the amount of reflected light and decrease the amount of transmitted light.

Thus, by changing the slope of the glass, you can mix the two colours in any desired proportions.

After practicing a while to get used to the procedure of the experiment, see what happens to the colour of the imposed images. For comparison, stagger the sheets a little so that an uncovered part should remain on each. Then you will see in the glass simultaneously the two initial colours and the result of their mixture.

To begin with, put a red sheet behind the glass and a white one in front of it. When the glass is perpendicular to the base the reflection of the white light will be very scant, but the red light will be transmitted almost fully. For this reason the colour seen in the glass will be bright

and pure, especially if the sheets are placed on black velvet.

Such a bright light is called saturated or pure in colorimetry.*

If the proportion of white light is increased, the resulting colour becomes whiter and whiter. Its saturation decreases as the glass is inclined more and more. Similar results are obtained if the experiment is repeated with the other coloured sheets.

These experiments suggest that mixing white light with a chromatic light lowers the saturation of the colour. As when we mixed black and white, a whole gamut of colours results, differing only in saturation. But though the colours in this gamut are different (and their number is infinitely large), the basic hue does not depend on the amount of white light added, the hue remains unaltered.

Now we can outline several parameters characterizing each separate colour in such a gamut. They are: the hue of the initial colour and the saturation of the colour. If we indicate the hue as before, by words, this will not be sufficiently clear. For that reason the initial hue is always related to the wave-length. Then everything becomes quite definite. Thus, the hue $\lambda = 400$ millimicrons means that the hue selected is the violet with the wave-length indicated.

As to the purity of the colour, it is given in per cent and shows how many units of a white light flux and how many of a light flux of the given hue are present in the resultant colour.

Now, what will happen if we mix two chromatic hues?

This can be ascertained with our apparatus. To begin with, put the yellow sheet in place of the white one. The resulting colours, depending on the slope of the glass, will vary from red to yellow, passing through various shades of orange. This is not surprising. One of the first things we find out in learning to paint is that on mixing red and yellow we get orange.

But can we always guess the result of colour mixture

* The hues of the solar spectrum, if regarded in a darkened room, are perfectly pure. The saturation of each hue in the spectrum equals 100 per cent. Strange as it seems, in colorimetry white light is the least pure: its saturation is 0 per cent.

from intuition and experience? Try to forecast the colours that result when we mix:

red	and	blue-green
yellow-red	and	blue
yellow	and	purple-blue
green-yellow	and	purple

Better write down your conjectures, especially if you are not doing the experiment all by yourself, and then check them with the apparatus. When checking, tilt the glass each time so that the resulting hue should not contain the initial hues. The experiment must be made carefully and with no bias as to the results. The latter should also be recorded.

I am afraid not one of the results will agree with the forecast. However, there is no reason to be upset about this. In science forecasts can be made only on the basis of theory. And we know none as yet.

But if you examine the results carefully, you will detect a fact that is very important for building this theory. All the pairs of colours selected, when mixed in a definite proportion for each pair, give the same colour. Moreover, that colour is grey, an achromatic colour, though the initial colours were chromatic in all cases.

Quite possibly, you will not succeed in obtaining real achromatic colours, but will see whitish dirty shades instead. But this is due to the fact that in naming the colours we continue to use their conventional names and that it is difficult to paint the sheets sufficiently well. But if we carry out such experiments with greater care the result will be quite definite—the ultimate colour will be white (or grey, depending on the brilliance). Knowing the results of the experiment, we can repeat it again, this time with greater success.

Experiments of this kind carried out by scientists were of very great importance. They showed that the structure of our eye is such that the sensation of white can be caused by mixing only two of the colours of the solar spectrum, and not necessarily all of them.

Of course, not every pair of colours gives white on mixing. This is evident from the example of red and yellow. Two colours which give white or any other achromatic

colour on being mixed in definite proportions are called complementary. There is an infinite multitude of pairs of complementary colours in nature, including monochromatic or spectrally pure colours.

To be sure your experiment succeeds the following pairs of pure spectral colours should be taken:

red	$(\lambda = 656\ \mathrm{m\mu})$	and blue-green	$(\lambda = 492\ \mathrm{m\mu})$
yellow-red	$(\lambda = 608\ \mathrm{m\mu})$	and blue	$(\lambda = 490\ \mathrm{m\mu})$
yellow	$(\lambda = 585\ \mathrm{m\mu})$	and blue	$(\lambda = 485\ \mathrm{m\mu})$.

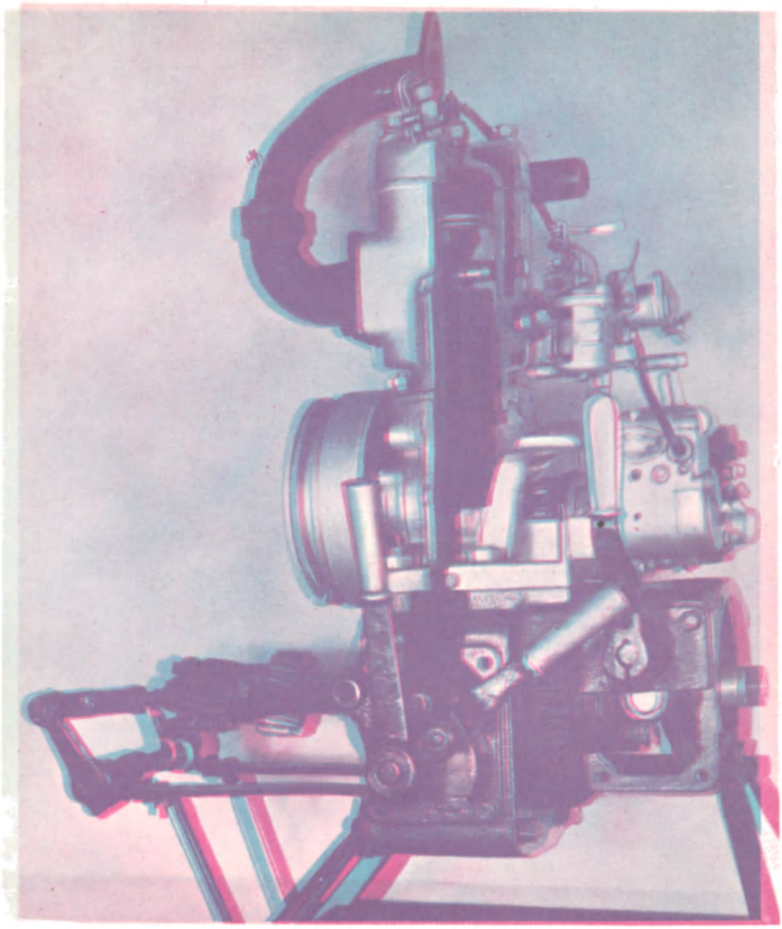
Amateur artists should pay special attention to the fact that complementary colours applied next to one another or one on the background of the other yield a strong and pleasing contrast. This property of complementary colours was guessed very long ago, in Renaissance times. And artists of the modern period resort to it purposely. For instance, the famous French artist Degas took advantage of this property even in drawings and achieved splendid effects. Degas often used toned paper with a green, pink, greyish-green or other tint, instead of white paper, and drew on it with a pencil of the respective complementary, or minus, colour, as it is often called, or tinted some parts of the drawing with the minus colour.

Those who like the fine arts will be interested in another fact. In any pair of complementary colours one always belongs to the warm group, and the other to the cold group. The warm hues are those which contain rays of red and orange, while the cold hues contain blue and indigo rays.

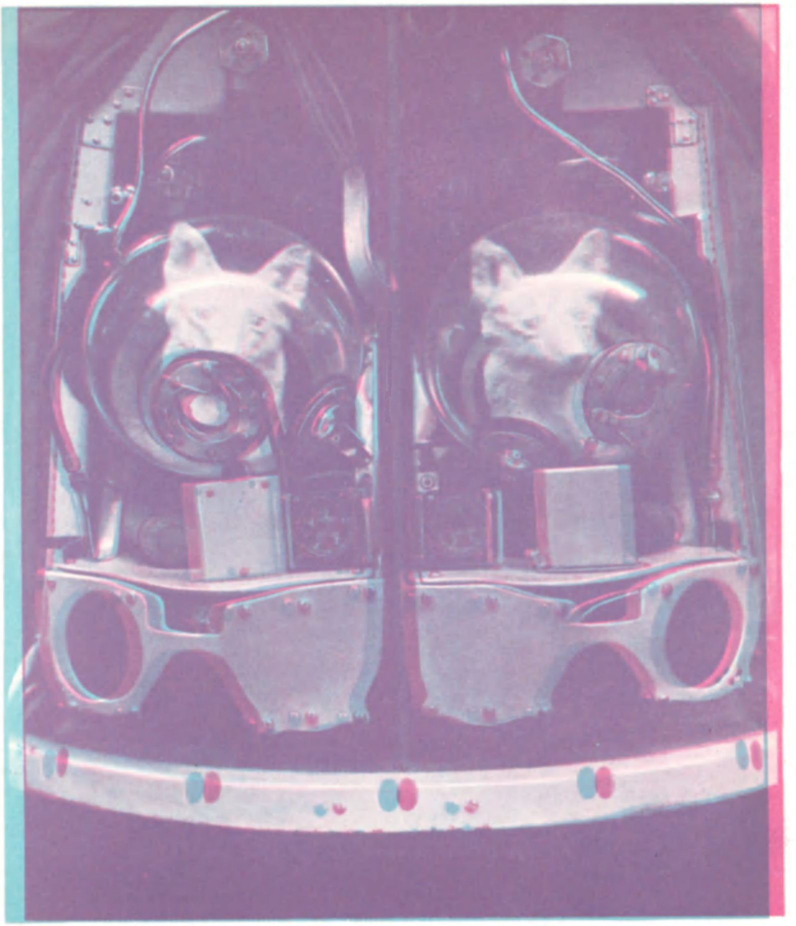
Can complementary colours be observed without the aid of special instruments? It appears that they can. One of the methods is based on the inertness of vision, rather on taking advantage of negative after images.

For example, after being for several minutes in the light of a blue lamp, ordinary light seems quite yellow. In recent years mercury lamps have come into wide use for street lighting. They give a very strong greenish light. When the eye gets used to this light the night city sky looks unusual: it acquires a violet tint. If we look through a piece of green cellophane for a while, and then remove it from the eye, everything seems pinkish coloured. Coloured after images

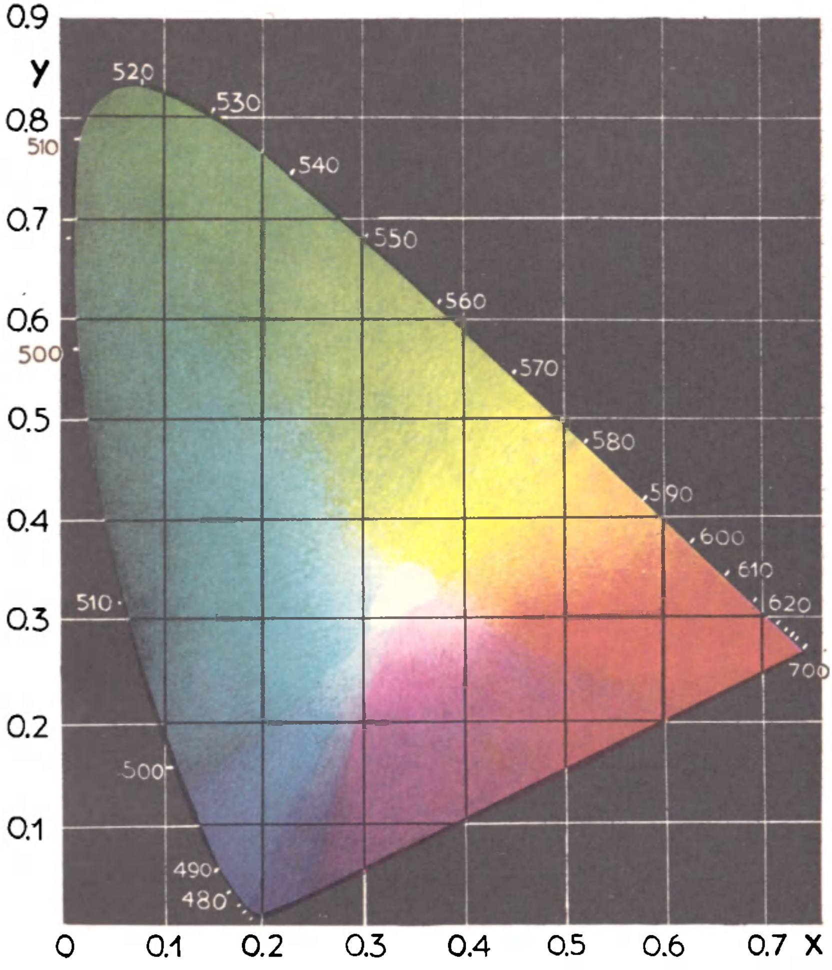
Put the book down before you, take a pencil in your hand and place it between the photographs. Now slowly bring the pencil closer following it with your eyes. When you see three photographs instead of two, carefully remove the pencil and continue to look at the middle one. Do this several times and you will finally see a stereoscopic image.



These photographs should be looked at through coloured spectacles. One lophane may be used



›f the glasses should be pink and the other bluish green. Sheets of cel-
'nstead of glasses.



Chromaticity chart. For better presentation the field of the chart is coloured. The chromaticity chart covers an infinite variety of colours and enables specialists to solve important practical problems.

can be observed by making use of the coloured sheets prepared for the above experiments. Turn your back to the light and holding a well illuminated sheet before your eyes, look at it intently for 30 or 40 seconds. Then shift your eyes quickly to a uniformly illuminated sheet of white paper. After a few seconds the negative after image will appear, hazy at first and hardly perceptible, then brighter and more distinct.

You should not be surprised if you find that its size differs from that of the coloured sheet. This change in size depends on the ratio of the distances of the coloured and white sheets from the eye. If these distances are equal, the sizes of the after image and the object will also be equal. If the white sheet is farther away, the after image will be enlarged and dimmer. But if the white sheet is closer to the eye than the coloured sheet, the after image will be diminished, and its apparent brightness is greater.* The best effect is obtained when the object (the coloured sheet, in our case) is viewed at arm's length and the white sheet is held about thirty centimetres away from the eyes. This will make the after image sufficiently bright. It is best to begin with the red or green sheet.

In the experiments where we mixed colours we had to do with colours of not very high saturation. Unfortunately, at home it is almost impossible to carry them out with pure spectral hues. Meanwhile, the latter give very interesting results. Thus, if we mix two 100 per cent pure spectral colours in certain proportions, the resulting colour will be less than 100 per cent saturated. In the extreme case, that is, when complementary colours are mixed, the saturation of the resulting colour will drop to 0 per cent. In other words, it will become white. True, there is an exception to this rule: when the spectral hues with wave-lengths of

* It would be good for those who wish to study the properties of the eye in greater detail to think this over and try to explain it. In doing so, take into account the laws of construction of the image in the eye, which were not mentioned here. As to the change in saturation of the minus colour of the after image depending on the distance, to explain this we must take into account the change in area of the part of the white sheet on the background of which we observe the after image, or on which it is projected.

from 575 to 700 millimicrons (yellow to deep red) are mixed they cause the sensation of a pure spectral colour of a wavelength within the range indicated.

There is one important group of colours in nature that is completely absent in the spectrum. These are the purples. They are mixtures of red and violet or red and indigo rays. Such a mixture yields very beautiful shades. We can get an idea of them by again resorting to our apparatus.

Thus, by mixing two chromatic colours or a chromatic colour with white we can obtain an infinite number of new colours. Can we obtain any of the existing colours in this way? Yes, we can. But to do this we must keep constantly changing the pairs of initial chromatic colours. If the pair remains unchanged, we can obtain an infinite gamut of colours, as we know, but not by any means the entire set of existing colours.

Scientists and artists have long been interested in the question as to the least number of invariable initial (primary) colours required to give all the other colours existing in nature by mixing in different combinations and proportions. Here is the answer to this question given by one of the most educated men of his time, the famous Renaissance architect Leon Battista Alberti (1404–1472):

"It seems obvious to me that colours take their variations from light, because all colours put in the shade appear different from what they are in the light. Shade makes colour dark; light, where it strikes, makes colour bright. The philosophers say that nothing can be seen which is not illuminated and coloured. Therefore, they assert that there is a close relationship between light and colour in making each other visible. The importance of this is easily demonstrated for when light is lacking colour is lacking and when light returns the colours return. Therefore, it seems to me that I should speak first of colours; then I shall investigate how they vary under light.... I speak here as a painter.

"Through the mixing of colours infinite other colours are born, but there are only four true colours—as there are four elements*—from which more and more other kinds of

* Elements - here—fire, air, water, earth.

colours may thus be created. Red is the colour of fire, blue of the air, green of the water, and of the earth grey and ash. Other colours, such as jasper and porphyry, are mixtures of these. Therefore, there are four genera of colours, and these make their species according to the addition of dark or light, black or white. They are thus almost innumerable....

"...Therefore the mixing of white does not change the genus of colours, but forms the species. Black contains a similar force in its mixing to make almost infinite species of colour. In shadows colours are darkened. As the shadow deepens the colours empty out, and as the light increases the colours become more open and clear. For this reason the painter ought to be persuaded that white and black are not true colours but are alterations of other colours...."

This long quotation from Alberti's work is adduced here to give the reader a better idea of how much was known to, or rather, brilliantly apprehended by the best people of the Italian Renaissance. Several hundred years have passed since Alberti wrote his "Three Books on Art"! Yet, how much of what he stated on the basis of his experience and striking power of observation was confirmed by science after almost five hundred years!

From the above quotation it follows quite clearly that four colours—red, blue, green and grey—are the principal ones and that all the rest are derived from them. This statement is close to the truth but still is not quite true. If the colours named by Alberti did not include grey, the famous architect could have been considered the founder of the modern theory of colour.

The first to point out the exact number of principal initial colours was M. Lomonosov. In this "Treatise on the Origin of Light, Presenting a New Theory of the Colours, Delivered at a Public Meeting of the Imperial Academy of Sciences, July 1, 1756" Lomonosov put forth the idea that all the colours could be produced by mixing only three initial ones. In confirmation of this, Lomonosov quoted the results of his numerous experiments on the subject.

The modern theory of colours and colour vision was created by Young and Helmholtz. A great deal was also done in this field by Maxwell.

The colorimetry of our days, based on the conception of three primary colours, is a harmonious science. It makes it possible to forecast exactly the results of mixing and determining the composition of complex colours. It made available to specialists a simple and reliable method of calculation suitable for the entire infinite variety of colours existing in nature. The three primary colours selected are the pure spectral hues: red ($\lambda = 700$ mμ), green ($\lambda = 546.1$ mμ) and blue ($\lambda = 435.8$ mμ).*

There is no need to dwell here on the theoretical details of colorimetry and the methods of calculation. The important thing is that the theory and practice of colorimetry are based entirely on the properties of human colour vision, determined by experiment and expressed in appropriate mathematical form.

In particular, these mathematical expressions have enabled scientists to draw up a comparatively simple chromaticity chart. Using this chart specialists can answer any questions related to the formation of colours. You can see this chromaticity chart in the accompanying figure. In principle, each point on the surface of the chart corresponds to one of the colours existing in nature. This chart differs from those used in practice in that a number of auxiliary lines have been left out, and to make it more vivid the artist has put the colours on it. Of course, he could not give an infinite number of them, but the general arrangement of the colours and their transitions are given correctly.

Up till now we have been speaking of the mixture of colours by adding various coloured light fluxes to one another. This method is known as the additive mixture of colours.

Another method is based on the merging in the eye of separate pure hues applied to a surface as minute points very close to each other. This method takes advantage of one of the properties of the eye, already known to us—acuity of vision. If the distance between the points and their size are such that the eye cannot discriminate them,

* Three other hues could be taken as the primary colours, but they must always be representative of the reds, greens and blues.

they merge into an integral spot the colour of which will depend on the hues of the separate points.

Certain artists have made use of this method of additive colour mixture, but in art it did not prove very fruitful and has been abandoned at present. In the textile industry, however, it is utilized very often: the cloth is made up of thin threads of various colours. As a result of additive colour mixture its hue differs from the colours of the threads. But the additive colour mixture method is probably used the most extensively in television. At present all systems of colour telecasting and many special-purpose colour television systems are based on this principle.

There have been attempts to use it for producing photographic film for colour photography and cinematography. Just before World War II such films even appeared on the market. But in later years the production of this type of film was abandoned. Today all widely used colour films are based on the method of subtractive colour mixture.

The possibility of forming colours by this method is a proof, in particular, of the existence of complementary colours. Indeed, what colour shall we see if we in some way subtract red rays from white light rays? We shall see the minus colour of red, namely, green.

The action of light filters is based precisely on subtractive colour mixture. Thus, with respect to a green filter, it may be said that it transmits green rays. But it is just as correct to say that it does not transmit red rays; that is, if it is in the path of white light, it subtracts all the red rays from it. Filters of other colours act similarly.

Theory indicates that subtractive colour mixture also enables all the colours to be produced from white light with the aid of three filters: red, blue and green. To obtain a new colour the density (light transmissibility) of each of the filters must be selected to make a definite proportion. When photographing on colour film this selection is made automatically.

Colour printing in the graphic arts, the use of water colours and certain other types of paints are also based on subtractive colour mixture. However, in these cases the processes of their formation are complicated by a large

number of additional factors precluding simple and exact forecasts of the colour of untried combinations. This often makes it necessary to resort to practical verification and tests.

From Facts to Theory

How to connect up the great variety of facts relating to colour vision? How to relate them all to the structure of the eye? And finally, how to explain the ability of our eyes to discriminate a multitude of colours and to sense so finely differences in shade?

The reader already has a general idea of the structure of the eye. He also knows a good many facts about colour vision. Until now only facts have been given on the structure of the eye and its properties, and they just had to be believed. But to get an insight into their interrelation, to understand why they are such, which of them are fundamental and which consequential, we shall have to make a brief acquaintance with theory.

It is considered to date, that the best theory suggested so far is that developed by Young, Helmholtz and Maxwell, known as the three-colour theory of colour vision. This name is not casual. The point is, that its starting point or basis consists in the assumption that the eye has three colour-sensitive receivers or elements, one of which reacts predominantly to red rays, the second to green and the third to blue rays.

According to the laws of colour mixture, each light-sensitive centre of the retina must contain all three types of receivers. Thus, if a red light ray falls on a given point of the retina, only the red-sensitive element is stimulated; at this moment the other two elements do not send signals to the brain. But if a composite chromatic light, say, yellow, comes to the eye, signals will be sent to the brain by two receivers, the red-sensitive and the green-sensitive. The sensation of white light is caused by all three receivers being stimulated strongly and simultaneously.

Practice, experiment are the best ways of verifying any theory. This holds true in the present case, too. Those who have grasped the phenomenon of additive colour mixture,

will readily appreciate that the three-colour theory is in good agreement with the facts. With the aid of this theory we can explain qualitatively and quantitatively the phenomenon of additive colour mixture, the existence of complementary colours and of colour after images.

In particular, this theory makes it possible to explain the reasons for a rather widespread defect of vision known as colour-blindness. Colour-blind people find difficulty in discriminating certain colours. Colour-blindness is no great rarety: its occurrence among men is as high as 9 per cent, but only 0.5 per cent among women. This defect is sometimes called daltonism after the famous British chemist Dalton who is mentioned in all textbooks on chemistry. But very few know that he suffered from this defect of vision, studied it thoroughly and described it in the literature and that this is the real reason it was named after him.

Most often, colour-blind people do not distinguish red and green but perceive the other colours quite normally. Now that we know about the three components and the three receivers of colour, we can assume that there may be people who do not perceive blue colours. Indeed, such people are encountered, but very rarely. Still rarer are people who do not distinguish colours at all.

We must warn our readers that very often colour-blind people do not even suspect that their vision is defective. Resorting to an analogy with sound perception, the colour-blind may be likened to people with a poor ear for music. In some cases colour-blindness may lead to grave consequences, especially in transport where red and green signals are commands of directly opposite meaning.

The best criterion of the truth of the three-colour theory is its successful application in engineering. It was on the basis of this theory that modern engineering developed colour photography and colour television, designed the latest light sources, brought to life colour printing and considerably extended the possibilities of the paint and varnish industry. Artists, who probably had a presentiment of it before anybody else, have also benefited and continue to benefit by it greatly.

The present-day theory of colour vision is rather old. It was formed mainly in the latter half of last century. In our days, when physics is undergoing continuous renewal, when theories are continually succeeding one another, its age seems very great and sometimes no less surprising than that of an old sporting record which has not been broken.

Why has this theory persisted for so long a time? Is it that it is true, or that insufficient attention has been paid to it?

Both conjectures are partly correct.

Though absolutely true theories do not exist, the present theory of colour vision has been able to explain to scientists and engineers practically all facts that have interested them to date. This shows that it may be considered correct.

But the second conjecture is also true to some extent. The theory of interaction between light and the eye has indeed not been in the centre of attention of physical science all these years. The chief trend of physics lay in the field of investigation of light as such, the atom, its nucleus and elementary particles. A few prominent naturalists did devote their efforts to establishing the interaction between light and the eye, but in the sum total of physical research these efforts constituted a small fraction, though the complexity of the problem they were solving can only be appreciated in the future. It might be added that this problem cannot be solved by physicists alone but will require the combined efforts of specialists in many branches of science, which until recently was also a complicating factor.

Perhaps, it is just as well that it happened so. Because future discoveries concerning the action of light on the human eye and nervous system may turn out so far-reaching and important that it may be advisable to leave them off for better times when such discoveries will be utilized only for the good of humanity and not for evil ends. It must be emphasized that such discoveries may not occur at all, but at the present-day level of knowledge the assumption that they are, in principle, possible cannot be regarded as pure fantasy. Just recently there was born a new science, called bionics. One of its tasks is the study of the sense

organs of man and animals in order to comprehend their structure and to create artificial sense organs to model them. For most animals sight is the principal sense and, naturally, it draws special attention. There is no doubt that this science will bring new, very interesting and important discoveries.

The three-colour theory of vision has persisted for so long without fundamental alteration because until now it has been able to account for practically all known facts and because it has justified itself splendidly in practice.

Besides, until just recently no serious facts were known which this theory could not explain. In other words, until recently there was really no need to reconsider it. But in the fifties new facts were discovered.

What facts were these?

First of all, that there was no solid proof of the existence of three colour-sensitive receivers in the eye, the assumption of which forms the basis of the three-colour theory. For many years attempts have been made to find them in the eye. It is known for certain that it is the cones that react to colour. Hence there arose the assumption that not all cones are identical, but fall into three types, one of which is sensitive to red, another to green and the third to blue rays. However, not all scientists were of this opinion: some held that all cones are identical, but that there are certain centres or chemical processes in them that react differently to different colours.

Numerous experiments have been performed to verify these assumptions. Their results were often very contradictory. And at times it appeared that conclusive evidence of the existence of three kinds of light-sensitive receivers was already in the hands of scientists. But upon verification it all turned out not so simple. At present many workers are no longer inclined to believe that the existing hypotheses—at least, as they are now formulated—are correct. Moreover, recent investigations have cast serious doubt on the very nature of light perception with the aid of visual pigments (iodopsin, rhodopsin). Today, many scientists even suggest that the photochemical theory of vision processes in the eye may be wrong.

For many years a very simple device or, rather, an amusing toy with surprising properties, has been known to scientists. This device, called the Benham disk, is a circle half of which is painted black; the other half of the circle has black double arcs of different radii drawn on a white background. Such a disk is given in Appendix II of this book. Cut it out, paste it on a piece of cardboard and make a top of it.

When you set the Benham disk spinning you will observe an unexpected phenomenon. The black-and-white disk will suddenly become coloured. Colours appear on its surface. They are weak and unsaturated, but quite perceptible. These colours are not constant: they change as the disk slows down.*

Several years ago British television experts, evidently on the basis of this phenomenon, performed a very interesting experiment. Once in the course of one of the programmes British viewers saw on the screens of their TV sets an advertisement of beef-tea cubes. It was a stationary image with very simple shapes. Nobody would probably have paid any attention to it, were it not that the image was coloured. The colours were faint, but distinctly visible. This advertisement drew the attention of the public—their televisors were ordinary black-and-white sets, not adapted to colour television.

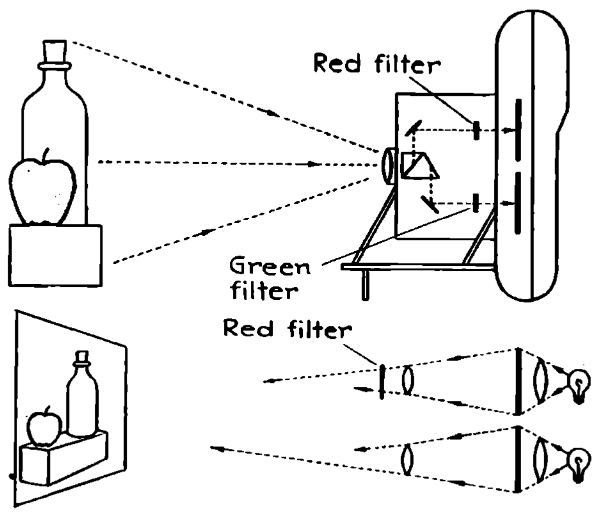
Any complete scientific theory must account for all the facts known to science in a definite field. This holds true with respect to the generally recognized theory of colour vision.

It also should have been able to account for the effect of the Benham disk and the experiment of the British engineers. But it has failed to do so, at least, up to the present. Of course, the appearance of colours on the Benham disk and the experiments of the British engineers may be regarded as a casual, uncharacteristic phenomenon, because in practice the light that acts on our eyes is always con-

* I have noticed that different people looking at the disk simultaneously see the colours somewhat differently. Check this among your friends. Also note how the arrangement of the colours changes when the direction of rotation is reversed.

stant, while the light coming from this disk pulsates. But this answer could satisfy science only up to a certain point, while the number of such particular cases was small, or until at least one case of substantial importance appeared. And had not such an important fact become known, we should have had to finish this chapter on vision by referring to this case as a particular and uncharacteristic one. But in the very beginning of 1959 the science of colour, which had been developing tranquilly on the basis of classical theory for many decades, was shaken by an event of prime importance.

It happened at one of the sittings of the U.S. National Academy of Science which was addressed by the physicist Edwin Land. The same Land who ten years before had invented a rapid photographic process which is employed



Land's twin camera (above) and twin projector. Two identical images are formed in the camera by means of a special system of prisms installed behind the common lens. For colour separation light filters are set up in front of the plates. The images are projected and superimposed on a common screen. The projector has two independent objective lenses.

now in some types of cameras. This time Land delivered a report on certain experiments in the theory of colour vision which he had been making with his collaborators for several years. The results were so interesting that it will be worth our while to tell about at least one of them in detail.

A special dual camera was designed for the experiment. It differed from a conventional camera in that the light flux passing through the lens was divided by means of a special device into two beams, each of which fell on a separate plate. The images obtained on both plates were exactly identical, because they were produced by a common lens simultaneously.

But there was a difference between them, consisting in that different filters were placed in the paths of the beams. One of these transmitted light rays of wave-lengths greater than 585 millimicrons, that is, orange and red, while the other allowed only rays of wave-lengths shorter than 585 millimicrons to pass, that is, part of the yellow, and all the green, blue and violet rays.*

Transparencies were made from the negatives obtained with this camera. We shall call the transparency obtained from the negative made in orange-red light, long-wave, and the other, the short-wave. Suppose the object for these photographs was a bouquet of red dahlias in a blue vase. If we examine the transparencies carefully we shall see that the shapes of the objects on them are exactly identical, but the gamut of greys differs. On the long-wave transparency the flowers are very light, while the leaves and vase appear almost black. On the short-wave one, on the other hand, the flowers seem almost black, while the leaves and vase are light. The intermediate colours of the object give different shades of grey on the two transparencies.

* If you want to experiment in this new and very interesting field, you can do so with an ordinary camera. Fix it firmly in place and take exposures of an immobile object, best of all, of a brightly coloured still-life. In this case the exposures will have to be taken successively: first, through an orange-red and then through a green or blue-green filter. Do not forget that different exposure times must be used with different filters.

Black-and-white photographs obtained by Land with his twin camera and light filters. Note the difference in these photographs.

Such negatives and transparencies are called separations (negative and positive, respectively), and are in themselves no novelty in colour photography and colour printing practice. True, the usual practice is to make three negatives using three filters: red, green and blue. Nor was what Land and his co-workers did with the transparencies anything new. They inserted them in a stereopticon projector and superimposed the images exactly on one another on a white screen. The result was a black-and-white image.

But this was not what interested the scientists. They projected the images from their transparencies in different colours: the short-wave one was projected through the same short-wave light filter, and the long-wave one through the long-wave filter.

Now (and this was the important point) they asked themselves what would happen if one of the filters were removed.

The answer was positively astounding. When Land removed the short-wave filter the picture on the screen remained multicoloured! The gamut of hues was not so rich as in nature, but the eye could distinctly discriminate various hues and shades.

What changed when Land removed the short-wave filter?

The only thing that changed was that the short-wave transparency was now being projected in white instead of bluish-green rays. But the long-wave transparency was still being projected in orange-red rays. Thus, only white and orange-red light rays were now incident on the screen, and no other rays. These rays mixed additively on the screen, but it is important that the proportion of orange-red and white was different at each point of the screen, depending on the degree of darkening of each of the transparencies at the point in question.

Earlier in this book we made experiments in additive mixture of colours and, in particular, of white and red, and we recall that on changing the proportion, only the purity or saturation of the red changed, but the hue remained red, as it had been.

Land was quite familiar with the laws of additive colour mixture. And, therefore, it is difficult to imagine the state

of mind of the researcher when these laws, which had lived unquestioned for so long a time, fell down in a heap before his very eyes (yes, precisely before his eyes).

What Land and his co-workers did when they hit on this discovery, we do not know. But we know very well what it made them do—work and work. It made them repeat their experiments again and again, disprove their own hypotheses and seek new evidence, new facts to account for this discovery. And to begin with, it was necessary to make sure there was no error in the experiment itself. The eye saw various colours where, according to theory, there should have been colours of only one hue, namely, orange-red.

This was what colorimetry asserted, what was borne out by years of practical experience, and—which is the main thing—by objective optical instruments by means of which the image on the screen was investigated. These instruments showed that (as might have been expected) only a mixture of white and orange-red light existed at any point of the screen.

But the human eye defied the instrument readings, theory and even logic, as it seemed: it saw different hues where there should have been none!

Here is what Land wrote about this:

"Is something 'wrong' with classical theory? This long line of investigators cannot have been mistaken. The answer is that their work had very little to do with colour as we normally see it. They dealt with spots of light, and particularly with pairs of spots, trying to match one to another. The conclusions they reached were then tacitly assumed to apply to all of colour sensations. This assumption runs very deep, and has permeated all our teaching, except for that of a few investigators....*

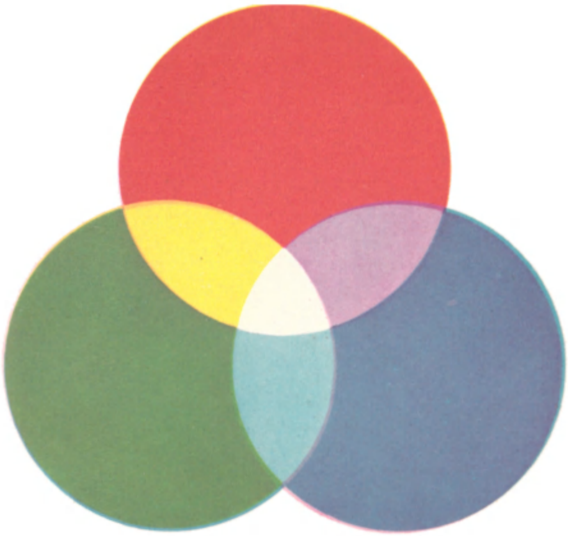
"The study of colour vision under natural conditions in complete images (as opposed to spots in surrounds) is thus an unexplored territory."

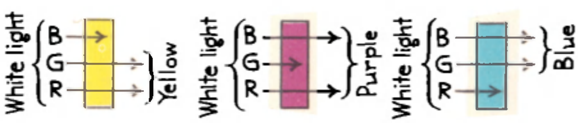
Not all scientists agree with Land as to the fact that his discovery cannot be accounted for in terms of the

* Who have studied the effect produced on a coloured spot by a coloured surround.

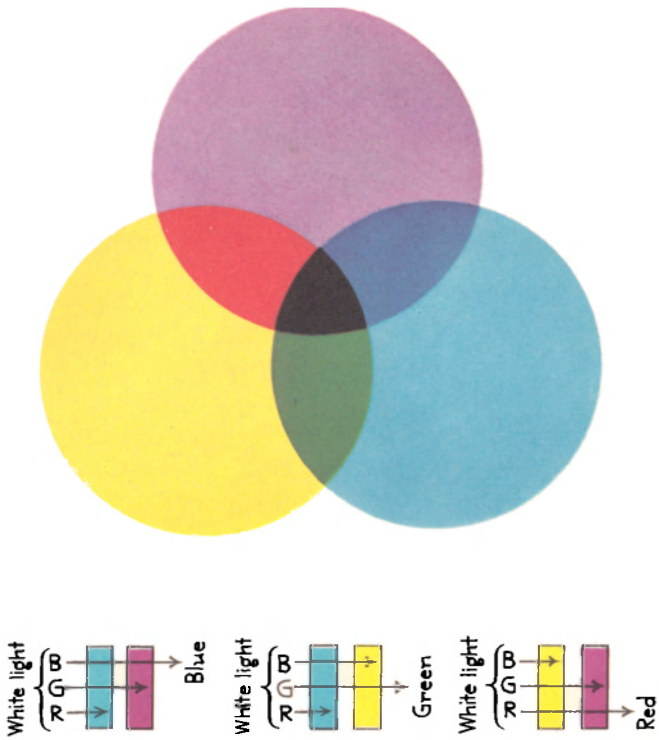
classical theory. Some time ago a number of scientists came forward with objections to Land's views.

It is early as yet to judge who will finally turn out to be in the right. But, be that as it may, all specialists agree on one point: these new facts are of major importance to science. Possibly, they will make it possible to understand the operation not only of the eye, but, what is especially important, of the visual centres of the brain and their interrelation with the other parts of the brain.

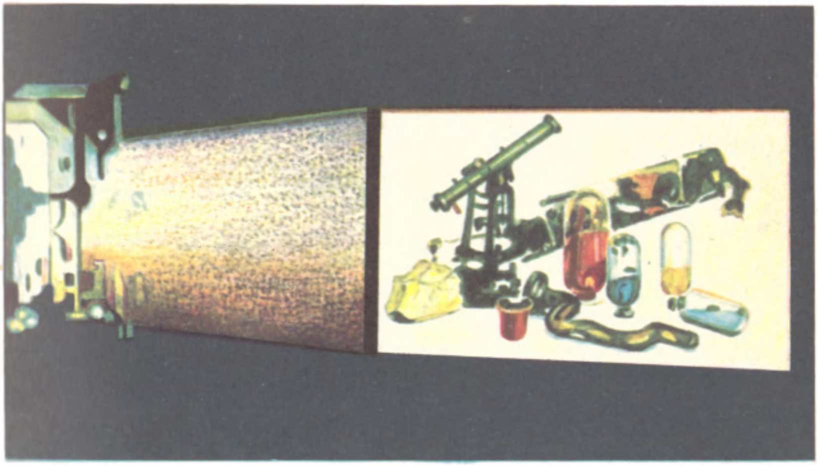




Additive colour mixture. Green plus red gives yellow. Red plus blue—purple; blue plus green—blue-green; green, blue and red together give white. If we pass white light through light filters we get colours. The yellow filter stops the blue rays; the green and red rays passed through the filter form yellow. The purple filter lets the blue and red rays pass through and stops the green ones. The blue filter stops the red rays and lets the blue and green ones pass through.

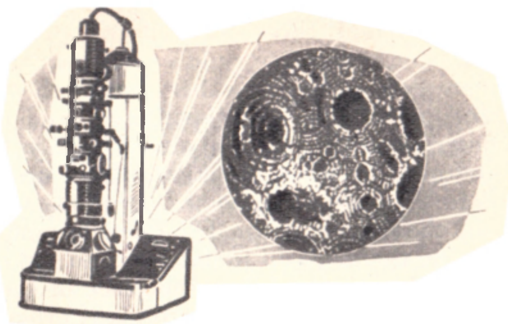


Subtractive colour mixture. When yellow rays are subtracted from purple, red results; when blue is subtracted from yellow the result is green; purple minus blue-green gives blue. If we subtract purple, yellow and blue-green rays from white light, we get black.



Formation of a colour image after Land.

Drawing of Mars. This is what the planet looks like to astronomers when observed through the best telescopes.



TELESCOPES AND MICROSCOPES

1600.... The beginning of an epoch of great social and scientific revolutions.

The beginning of the century which brought into the limelight of science the names of Galileo, Huygens, Descartes, Kepler, Leibnitz, Newton. These men did so much for science that grateful posterity has had good reason to set up monuments in their honour. But no monument has probably been put up to the nameless Dutch glass grinders whose hands fashioned, in the beginning of that same XVII century, the first telescope and the first microscope—tools of prime importance to science over a period of many, many years.

It is difficult to imagine what would have happened, had not these great inventions been made in the XVII century. Of course, they would have been made anyway, sooner or later. But the names of the scientists mentioned above might not have gone down in history at all then, because the scientific merits of most of them are connected in one way or another with the knowledge they acquired through the telescope.

More than three hundred and sixty years have passed since the inquisitive child's eye looked through two lenses placed one before the other. During these years many great discoveries and inventions have been made, which have determined the aspect of our life today. But not all of them continue to serve mankind. Many are hopelessly out of date. The steam engine has given way to the steam turbine and the electric motor. The steam locomotive is being forced out by the more up-to-date electric and diesel locomotives. The teletype has taken the place of the Morse telegraph key. And in the near future many other inventions, which have been very useful in their time, will also go to rest.

But the telescope and the microscope are destined to stay with us a long time yet, most probably, forever.

Of course, modern optical instruments have changed greatly compared to their "forefathers", but their working principle has remained the same. What has changed sharply is their accuracy and quality of manufacture, and therefore, the possibilities they offer.

Telescopes

All our knowledge of celestial bodies is brought to us by light. It is the only bridge connecting the Earth with the great Universe. Caught by telescopes and imprinted on drawings, photographic plates and star maps, light has made it possible for astronomers to amass a great deal of knowledge and to form the first serious theories of the origin and structure of the Universe.

We are the eye witnesses of the beginnings of a new astronomy, the astronomy of the epoch of space voyages. An epoch in which mankind will start a direct investigation of many celestial bodies. Not so much time has passed since the first sputnik was launched in the Soviet Union, but during this short period scientists and engineers have made great progress indeed. Their achievements have surpassed the most daring forecasts of experts, who greatly underestimated the possibilities of modern rocket technique and the rate of its progress. For example, it was thought in the mid-fifties that it would take about one hundred years after the launching of the first man-made satellite before a

man could be landed on the Moon; at present it can be stated confidently that we shall witness this great event in the seventies of this century.

Such great successes have led some people to think that now that the era of direct investigations has come, the telescope will in time cease to be the principal tool for studying the Universe, because journeys of men to the stars, and the more so to other planets, will make it unnecessary.

This is a mistake.

There is no doubt that men will visit the planets, evidently, beginning with Mars. And we would very much like this to occur during the lifetime of the creators of the first sputnik. But the largest planets of the solar system will, unfortunately, remain inaccessible to mankind for many years to come. The principal means of defense of these planets against invasion by men from the Earth is their immense gravity. For instance, on Jupiter, the largest planet of the solar system, all bodies have three times more weight than on the Earth. Even in the absence of other obstacles,* the landing of a rocket on Jupiter and its return at least to one of the satellites of that planet will hardly be possible in the next few decades, owing to the very great force of gravity. As to visiting or even flying close by any of the stars, such an expedition will never be possible—this becomes clear as soon as we recall the temperatures existing on the surfaces of the stars.

Thus, the telescope will long remain one of the most important tools for carrying out most astronomic observations and investigations. But this does not signify by any means that the development of rocketry will have no effect on these investigations. It has already begun to tell on them. And we shall have a few words to say about the first results.

It is often said that the telescope magnifies the objects observed. This is wrong. The image in the telescope is always smaller than the celestial body observed. It is more correct to say that the telescope increases the angle at which

* It may happen that Jupiter has no solid ground at all, that is, that the outer layers of its surface are not dense enough.

the object is observed. In other words, a telescopic image has a larger angular size than that seen by the naked eye. The telescope brings the observed object closer to us, as it were. However, such magnification is not always possible even with the largest telescopes. And here is why.

Objects of astronomic observation fall into two categories depending on their angular size. The first includes all celestial bodies whose angular size, defined as the ratio of the diameter of the body to its distance from the Earth, is fairly large. Such are, primarily, the Sun and the Moon, which are visible at an angle of 0.5°. This category also includes the planets, though their angular sizes are much smaller: 57″ or 0.0158° for Jupiter, and not over 19.2″ or 0.00535° for Mars. Many galaxies are also visible at large angles, even much larger than the Sun and the Moon. For instance, the Andromeda Nebula, or rather, its main body has a width of about 40′ and a length of about 160′. However, the distance to it is so great that its luminance corresponds to that of a star of the ninth magnitude. And even to the eye aided by a telescope, it seems not a very bright star. Its distinct image can be obtained only by photographing with a long exposure time.

The second category—the so-called point objects—is very numerous. It includes all the stars. The closest of them is so far away from us that the numerical value of the ratio of its diameter to its distance from Earth is very minute. Even at the maximum theoretically possible magnification of a telescope a star will still look like a luminous point, just as when observed by the naked eye. The telescopic image of a star differs only in that it is brighter and has none of the rays we observe for bright stars.

Thus, when observed through a telescope the objects of the first group become larger in angular size, and details become discernable on their surfaces, which are invisible to the naked eye; but the angular size of point objects remains practically unchanged.

Then why use a telescope to observe them?

Before answering this question, let us put astronomy aside for a moment.

Have you ever collected rain water in the open? To do this one usually puts out under the rain pails, troughs,

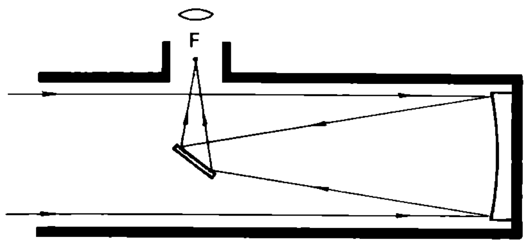
basins. But it would never occur to anyone, even though he knew nothing at all about physics or mathematics, to put a bottle out in the rain for this purpose—everybody knows that too few drops would be caught in its narrow neck.

It is much the same when observing the stars.

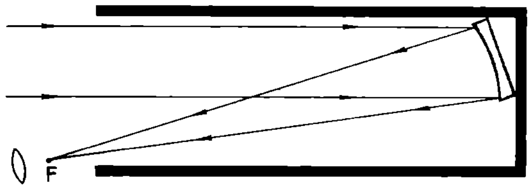
All the rays coming to Earth from any particular star have practically the same direction. In other words, the paths of all the photons speeding from that star to Earth are parallel. An optical system placed in the path of such a photon "shower" changes the path of each of them so that all the paths intersect at one point. In the eye this point (the focus) is on the retina, and in a telescope it is in the focal plane, where a photographic plate is usually placed. The light quanta captured by the entrance pupil of the optical system yield their energy to the rods and cones in the eye, or to the light-sensitive grains of emulsion, or the rods and cones of the observer's eye in the case of the telescope.

Very few photons are caught by the naked eye, but the number of them falling on the photographic plate or the observer's eye when a telescope is used is much greater. This is natural. The maximal diameter of the pupil of the human eye is not over 8 millimetres. And, therefore, the area over which the eye collects the drops of the light "shower", that is, photons, is about 50 square millimetres. On the other hand, the entrance pupil of one of the telescopes built in the U.S.A. has a diameter of 5,000 millimetres, and its area is 19.6 square metres. The area ratio of the two pupils shows that the telescope collects 392 thousand times more photons per unit time. Under the most favourable conditions a good observer can see stars of the sixth magnitude with the naked eye. With the aid of a 5-metre telescope he can see stars of the 18th or 19th magnitude.

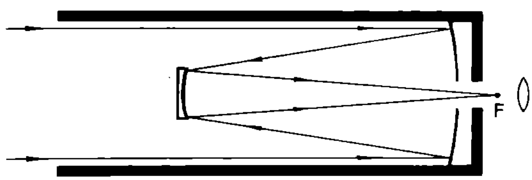
In our case the naked eye can be compared to a narrow-necked bottle, and the telescope to a huge tank. And, to continue this analogy, when observing through a telescope, the eye may be compared to a bottle and the telescope to a funnel with a very wide mouth which collects all the drops —photons—and "pours" them into the small aperture of the eye.



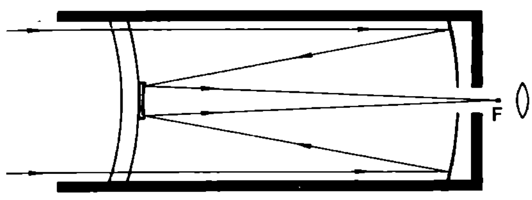
Newtonian



Lomonosov-Herschelian



Cassegrainian



Maksutov

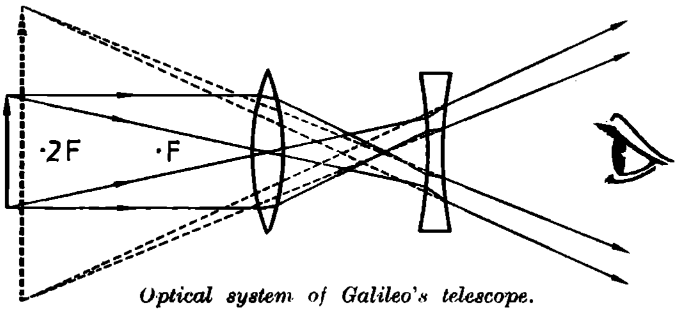
Optical systems of telescopes.

In our times astronomers rarely look at the stars. The observer has quite long since given up his post to the photographic plate. This is more convenient for a number of reasons, but two of them are probably more important than the rest. First of all, photographing is better because each photograph is a very authentic document which records forever the most exact data as to the arrangement of the observed objects, their radiance and configuration at the moment the exposures were made. Changes taking place in the skies can be detected by comparing photographs of the same part of the sky made at different times. Secondly, photography makes it possible to detect stars and other objects which are too faint to be observed by the naked eye. This is due to the ability of the light-sensitive grains of the emulsion to add up or accumulate the photochemical action of photons in time. The ability of the eye to accumulate consecutive stimulations of separate photons is much less developed. Besides, if the number of photons falling on a given rod per unit time is smaller than a certain minimum (below a certain threshold) the eye will not perceive the light at all.

The "passport" of each star includes not only its photograph, name and address. It also records the distinctive marks of this citizen of the Universe: its radiance (a value characterizing the brightness of the star) and spectral type. Special instruments used jointly with the telescope—photometers and spectrographs—help to determine these marks. The spectrograph is used to photograph the spectrum of the star, and the energy distribution in the spectrum is studied by means of very sensitive thermometers—thermocouples.

In our days astronomers have telescopes of various types and classes at their disposal. Some of them are designed for investigating the farthest accessible depths of the Universe, but have a very small angular field of view; others cannot penetrate so far into space, but enable fairly large areas of the sky to be photographed.

With regard to working principle or, rather, optical system, telescopes may be divided into three main groups: refractors, reflectors and mirror-lens telescopes. The first telescopes were those in which a converging lens was used as the objective and a diverging lens as the eye-piece. Such



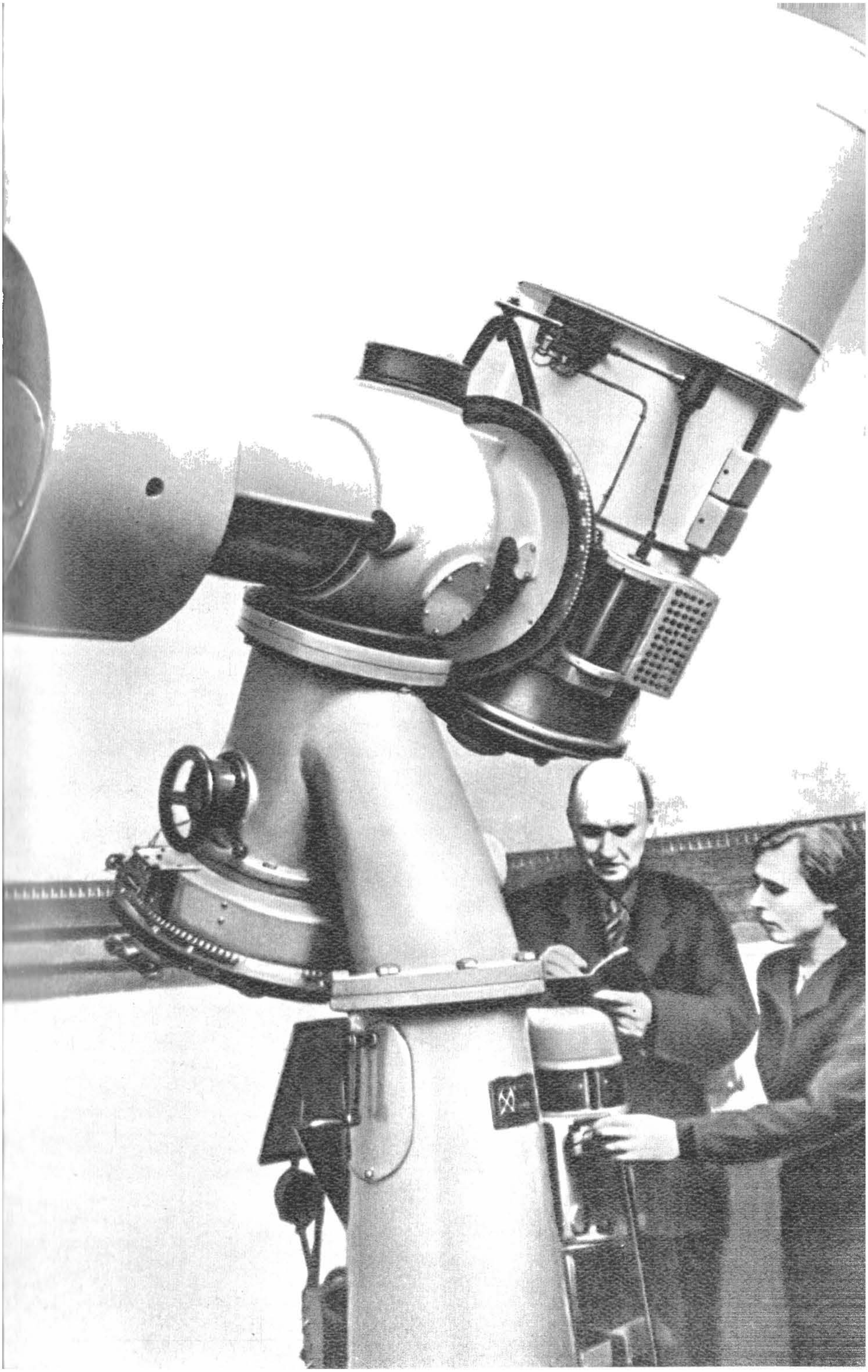
Optical system of Galileo's telescope.

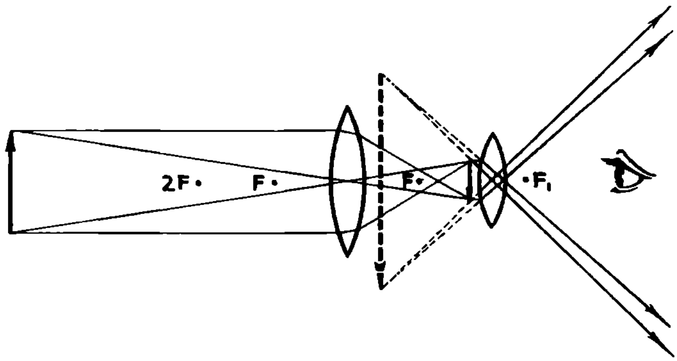
was the system of Galileo's telescope. Kepler designed and used a different optical system which is the one now employed in refracting telescopes. In this system both the objective and eye-piece are converging lenses.

The first telescopes gave very imperfect coloured images. Newton found the reason for this defect and even came to the conclusion that image colouration could not be eliminated in refractors. This was a mistake. However, it had not only harmful, but also useful consequences: it prompted Newton to design a telescope after an entirely different optical scheme. He made such a telescope with his own hands in 1668. This was the world's first reflector—a telescope which uses a concave mirror as its objective instead of a converging lens. Images in a reflector are not coloured by virtue of its design, because the light does not pass through a lens, but is reflected by a polished specular surface.

True, the idea of the reflector was not Newton's; it had been suggested five years earlier by Gregory, a countryman of the great physicist, but Gregory's optical system differed slightly from that proposed by Newton. That is why the latter is usually credited with the honour of inventing the reflector. Actually, he was the first to make a reflecting telescope. Gregory was unlucky: after Newton had already made his telescope, an optical system similar to that suggested by Gregory was described anew by another scientist, Cassegrain. And this system is still often known as the Cassegrainian system.

Maksutov telescope and its inventor.





Kepler telescope.

Newton's mistake was corrected only in 1729, when the first achromatic objective lens appeared. From that time on refractors regained their recognition.

At present both types of telescopes are built and employed. Each has its advantages and disadvantages; each is used to solve its own specific range of problems: refractors for astronomical observations and investigations, and reflectors for astrophysical work, e.g., for spectral investigations.

Just recently there appeared a new type of telescope, invented by the Soviet scientist D. Maksutov. The optical system of this telescope is a combination of a diverging lens or meniscus and a spherical concave mirror. The advantages of this type of telescope are simplicity and the very small length of the instrument.

At present reflectors are the more powerful instruments. The main mirror, the largest in existence, is 508 centimetres in diameter. This telescope is installed in the observatory on Mount Palomar, California, U.S.A. The diameter of the object glass of the largest refractor is only 102 centimetres. This means that the largest reflector makes it possible to collect 25 times as much light as the largest refractor.

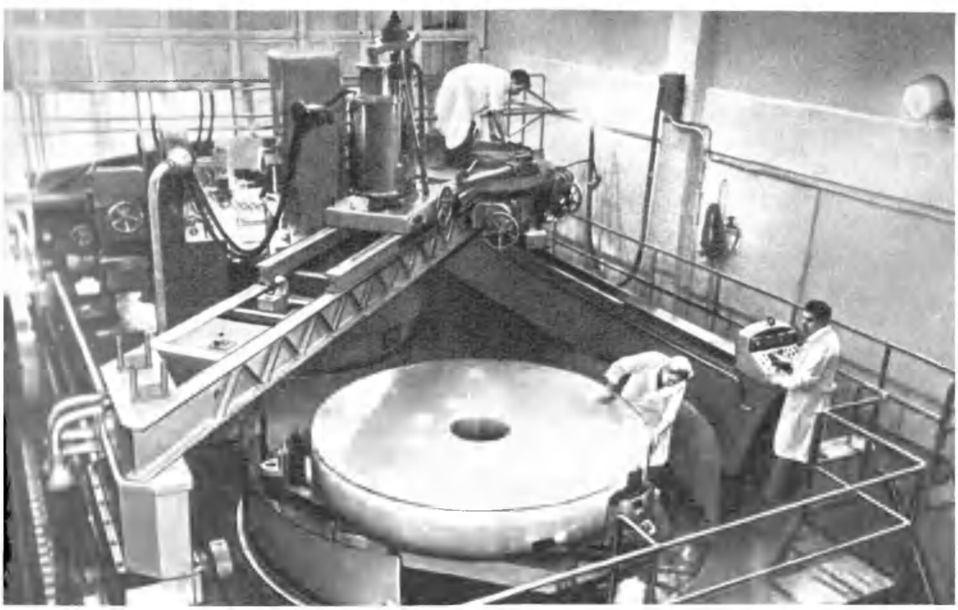
Not long ago a reflector was built in the U.S.S.R. with a mirror 260 centimetres in diameter. It was installed in the Crimean Astrophysical Observatory.

The largest refractor in the U.S.S.R. is that of the Pulkov Observatory: the diameter of its objective is 75 centimetres.

You can judge by the photographs what an immense and complex structure a modern large telescope is. Besides high optical qualities this great structure must possess facilities for pointing at any desired part of the sky, and must be able to rotate just as smoothly and uniformly as the globe in order to follow the position of any selected star with very great accuracy. The construction of such telescopes takes years and is very expensive.

Not long ago, before the epoch of rockets and man-made satellites, many people thought astronomy to be a science that had little to do with life. Nowadays, the attitude of the uninitiated towards it has changed, but they still think astronomy will be of practical use only in the future. This is wrong. Astronomy is not only a science of the future, it is at the same time one of the most ancient sciences. And it appeared in order to supply answers to questions of vital interest to the human race. It was successfully practised by the high priests of Egypt and Mesopo-

Grinding a mirror 2.6 metres in diameter at the Leningrad Optico-Mechanical Works. This operation took more than a year and had to be carried out at a strictly constant temperature.



tamia, and by the priests of the Mayas, Incas and Aztecs in the Western hemisphere.

Astronomy was not only of mystical significance to the ancients, did not serve only to consolidate the priests' power. Its chief designation was purely practical and exceedingly important—it gave the peoples the calendar.

We are apt to take the calendar for granted, as an eternal phenomenon inherent in nature itself. But this is not so, by any means. The calendar is one of the most important inventions of antiquity, made on the basis of knowledge of the laws of alternation of the seasons and celestial phenomena. It was the calendar that made it possible for people to carry out agricultural work in time.

The most accurate calendar, as was established recently by scientists, was that of the Mayas. Though their time reckoning was based on other lines than ours, they determined the duration of the year more accurately than any other people. The year lengths indicated by different calendars are compared in the table below:

Julian calendar	365.250.000 days
Gregorian calendar	365.242.000 days
Mayan calendar	365.242.129 days
Exact astronomical data	365.242.198 days

Even today, the life of any people is governed to a certain extent by the calendar. There are days when the calendar orders us to be merry, others are considered days of mourning. All this is the heritage of olden times, when the high priests, and later the clergy, demanded strict observance of calendarial instructions.

Astronomy received further development in connection with the rise of a new problem of great importance for humanity—navigation. This happened when sea-faring began to develop. Only the stars could serve as waymarks to ships far from shore, and seafarers willy-nilly had to become astronomers as well. A knowledge of certain branches of astronomy is indispensible to present-day navigators, too. Navigation by the stars—astronavigation—is of vast importance in our days.

Modern astronomy was born during the late Renaissance, when the human mind for the first time in many ages broke through the yoke of clerical obscurantism. In 1543, the year of the death of the great Polish astronomer Nicolaus Copernicus (1473-1543), the latter's book "On the Revolution of Celestial Spheres" was published. Copernicus's book dealt a shattering blow to the Aristotelian picture of the Universe sanctified by the ages and by the Roman Catholic Church.

Copernicus's views were consolidated in the early XVII century, when Galileo made his universally known observations. Here is what Prof. G. Bernal writes about this in his "Science in History":

"The bare news of it (the telescope—*A.S.*) reaching the ears of the professor of physics and military engineering at Padua, Galileo Galilei, determined him to make one himself and turn it on the heavens. Galileo was already a convinced Copernican, as well as being deeply interested in the movements of pendulums and the related problems of the fall of bodies. In the first few nights of observation of the heavens he saw enough to shatter the whole of the Aristotelian picture of that serene element. For the moon, instead of being a perfect sphere, was found to be covered with seas and mountains; the planet Venus showed phases like the moon; while the planet Saturn seemed to be divided into three. Most important of all, he observed that around Jupiter there circled three stars or moons, a small-scale model of the Copernican system, which anyone who looked through a telescope could see for himself."

In our days astronomy is essentially not one, but several sciences united for a single purpose. It includes celestial mechanics, which studies the laws of motion of celestial bodies; and astrophysics which investigates the physical processes and chemical properties of celestial bodies and interstellar matter; and cosmogony, a science which strives to solve the mysteries of the origin and development of celestial bodies; and even astrobotany, a new branch of astronomy, dealing with the vegetative covers of Mars.

Astronomy is one of the few sciences that has drawn numerous amateurs for ages past. They have not infrequently succeeded in making very valuable observations. Ama-

teur astronomers of different countries afforded great help in observing the flight of Sputnik I. True, amateurs still experience difficulties in purchasing good instruments. Telescopes for amateurs are still very expensive. However, let us hope that with the further development of the optical industry they will become cheaper. And then amateur astronomers will be no less common than radio amateurs or amateur photographers.*

One of the most important divisions of astronomy is the study of the planets of the solar system. Since long ago they have attracted the attention of astronomers both because they are more accessible for observation, and because scientists have long felt them to be closely akin to the Earth.

These presentiments were confirmed when Lomonosov discovered an atmosphere on our closest neighbour, Venus. Unfortunately, it is not very transparent, so that we still know much less about this planet than about the more distant Mars. The study of Venus is also complicated by the fact that it is closer to the Sun and is therefore less convenient to observe than Mars.

* In his book "The Possible and the Impossible in Optics" G. Slyusarev tells how to make a simple telescope.

"For the object glass you can use a converging spectacle lens of from 2 to 4 positive dioptres (for long-sighted persons), and for the eye-piece – a strong positive magnifying glass, each with a focal distance of 3 or 4 centimetres. Arrange them one behind the other with their convex sides inwards. Rim the lenses with cardboard and insert them in two tubes (a long one for the objective and a short one for the eye-piece) so as to enable focussing for far and close distances.

"If the object glass aperture is diaphragmed to 2 or 3 centimetres this telescope will give fairly good images of the luminaries. With it you can observe the walled planes on the Moon, Jupiter and its four satellites, the Andromeda and Orion Nebulae, etc. If the focal length of the objective is 50 or 100 centimetres and the atmospheric conditions are favourable, you can discern, if not the rings of Saturn, at least the indistinctly shaped formations first noticed by Galileo with a telescope of about the same quality. It is commonly known that Galileo died without having found out what these formations were. His failure to do so must probably be attributed to ... diffraction."

The spectacle lenses used in "fashionable" rims are not much good for such a telescope. It is better to use a circular well cut lens.

But this planet is closer to Earth than Mars, and that is why the first automatic interplanetary stations carrying various scientific apparatus were sent in the direction of Venus rather than Mars.

The study of the planets with the aid of space stations has just begun, and the scientific results are still rather scarce. But one thing is doubtless—that investigations of this kind will enable scientists to make new discoveries of importance not only to astronomers, but to those who study the Earth as well. When we have studied the features of our closest neighbours we shall be able to understand our own planet better. We shall get a better insight into the processes taking place in our atmosphere, and maybe we shall be able to understand the origin of the magnetic field of the Earth.

In the near future men will be able to send automatic stations to Venus and other remote planets, which will land on their surface, making it possible to investigate them directly. And then we shall be able to find out whether there is any life, even of the most primitive kind, on the

This picture was made in the joyous days of October 1957 when the first man-made satellite in history was launched. Amateur astronomers afforded great help to scientists in those days.

planets of the solar system, and to study these cosmic forms of life. And, of course, scientists would do their best to obtain an exact map of each of the planets.

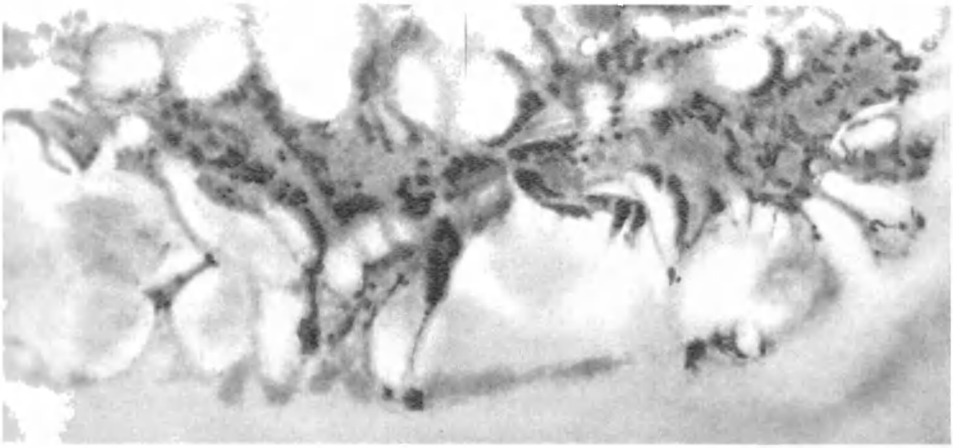
An exact map of a planet.... This would indeed be a priceless acquisition for our terrestrial science. It would give us material by which to judge not only of the other planet, but to find out new things about our own as well.

And it is not without reason that so much attention is directed towards the study of the surface of Mars. Investigations of this planet became especially extensive after the Italian astronomer Giovanni Virginio Schiaparelli (1835-1910) observed a strange pattern of intersecting thin lines on its surface. He interpreted these lines as structures built by intelligent creatures, and called them canals. This interpretation was probably an expression of humanity's cherished (perhaps subconsciously at times) dream of finding intelligent creatures in other worlds. And that is most likely why the news of Schiaparelli's discovery attracted so much attention.

In the years following this discovery the question of the Martian canals was a point of very serious arguments among astronomers. At present, however, they have come to the conclusion that most probably there are no formations resembling those seen by Schiaparelli on the surface of Mars at all. But this is not final.

It is believed that the most feasible explanation of the Martian canals is that they were an optical illusion. Such illusions appear when weakly illuminated objects are observed at the threshold of visibility. Another fact in favour of this version is that Schiaparelli's telescope was not a very large one, and was subject to strong diffraction.

As larger and larger instruments became available to astronomers, in which the image of Mars became brighter and diffraction was of less account, the canals came to be observed less and less frequently. In modern large instruments they are not to be seen at all. You can convince yourself of this by looking at the map of Mars drawn up at the Pic du Midi observatory during the opposition of Mars in November, 1958. Mars was observed with a 61-centimetre refractor at a magnification of 1,200 $\times$. The angular size of the image of Mars was therefore $19.2'' \times 1{,}200 = 6.4°$. This



A map of Mars drawn during the opposition of 1958.

is the angle at which you would see a half-dollar coin held 22 centimetres away from the eye. Besides the map of Mars you will find in this book one of the latest drawings made of it (Mars comes out bad in photographs, and observers still draw it). The map and drawing give some idea of what Mars looks like to astronomers. It can be seen from the drawing that there are no canals on Mars. Either they disappeared in the course of the sixty years that have passed since Schiaparelli made his discovery, blown over with sand storms, or, and this is almost beyond doubt, they never existed.

In our time scientists believe that there are no intelligent creatures on Mars. On the other hand, they have almost no doubts as to the existence of vegetation there. Numerous photographs of Mars's surface made in various spectral rays, and other spectral investigations carried out by Soviet astrobotanists under the guidance of G. Tikhov give grounds to consider this an established fact.

A great deal of attention is devoted by astronomers and astrophysicists to the study of the Sun—the only star sufficiently close to us. The physical processes on the Sun, studied by scientists, make it possible to delve deeper into the mystery of matter and nuclear reactions. These processes exert a great influence on the state of the Earth's atmosphere, on the weather and on radio communications.

By studying the Sun scientists will come to know other stars better.

The Sun is studied by various methods: photographs are taken of its spectrum, of its visible surface in light rays of different wave-lengths, investigations are made of its corona. In all these investigations the chief instrument is the telescope.

The prominent British astrophysicist Sir James Hopwood Jeans (1877-1946) described the Sun as follows:

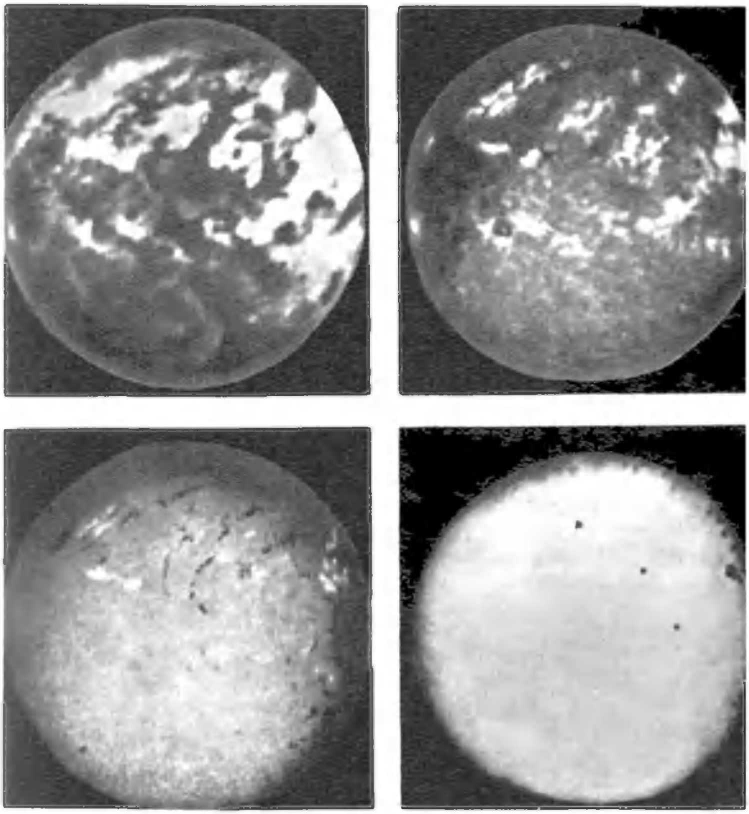
"It is clear that the Sun is no dead world like the Moon or Mercury. On the contrary, nothing is ever at rest here; everything is in a state of frenzied motion; the whole surface is excited, boiling, seething and erupting in various ways. We understand why this should be so.

"The inside of the Sun is like a huge continuously operating power station. The energy liberated inside the Sun makes it exceedingly hot so that an immense flow of heat is thrown outwards to the surface, and then poured into space as radiations.* Naturally, the surface cannot remain calm through all this, and we see it boiling all over. The outer layers simply keep rolling over turning their hotter sides towards outer space, to allow faster liberation of the radiant energy stored in them.

"But this is not all. Huge fountains of flame, called prominences shoot up here and there to heights of hundreds of thousands of kilometres above the solar surface. They are mostly crimson-coloured and often of the most fantastic shapes. Some of them almost stand still, others let out side branches at a rate of thousands of kilometres per second. Some of them break away entirely from the Sun, and rise hundreds of thousands of kilometres....

"The fantastic architecture of crimson flame of the prominences is not the only decoration of the Sun's surface. In various parts of it we see dark gaping hollows resembling the craters of live volcanoes, retching out fire and substance

* The total irradiation of the Sun per second constitutes the tremendous sum of 9×10^{25} calories, a figure with 25 noughts. If we convert this figure to its mass equivalent, using Einstein's formula for the relation between mass and energy, we find that the mass of the Sun decreases by 3,170 thousand tons each second!

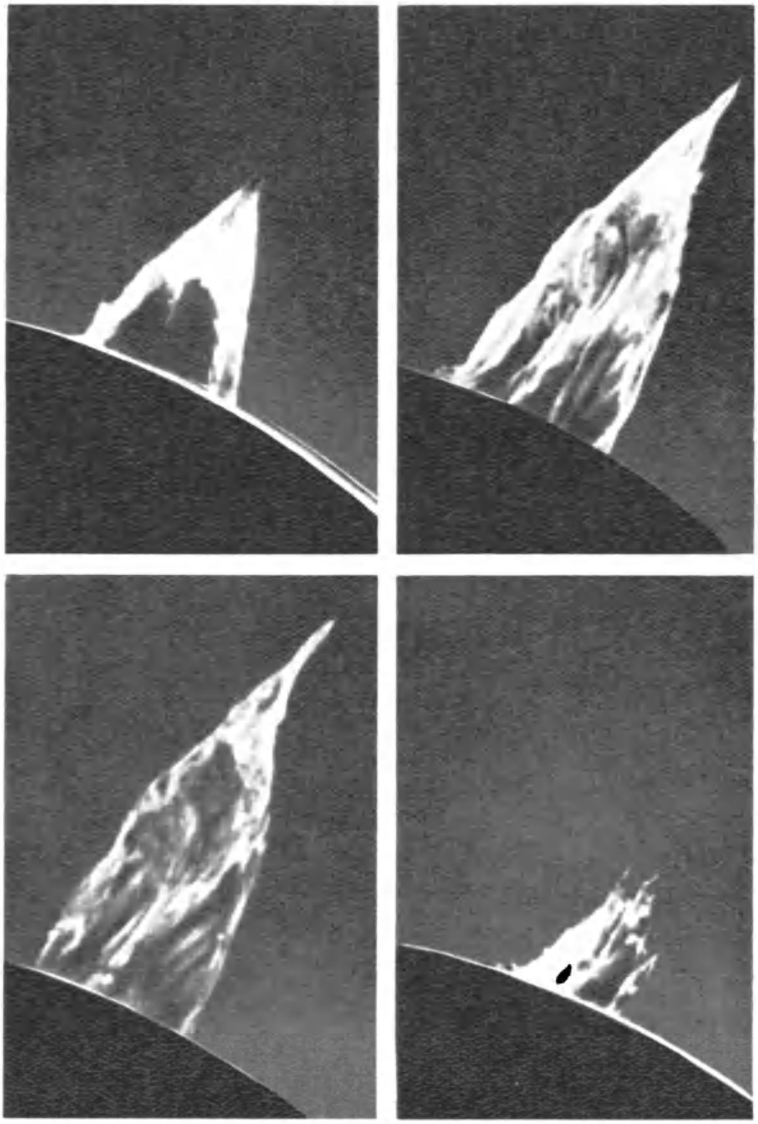


Photographs of the Sun taken through special light filters transmitting light of practically one wave-length: 1—in ultraviolet rays; 2—in blue rays; 3—in red rays; 4—ordinary photograph of the Sun in white light rays, for comparison.

from the depths of the Sun. On Earth we call these hollows Sun spots...."

In the photographs given in this book we can see pictures of the Sun taken at various wave-lengths, as well as four consecutive pictures of a gigantic solar explosion.

From the sun the path of astronomy leads to the stars and the distant worlds of the Universe—the galaxies. Their

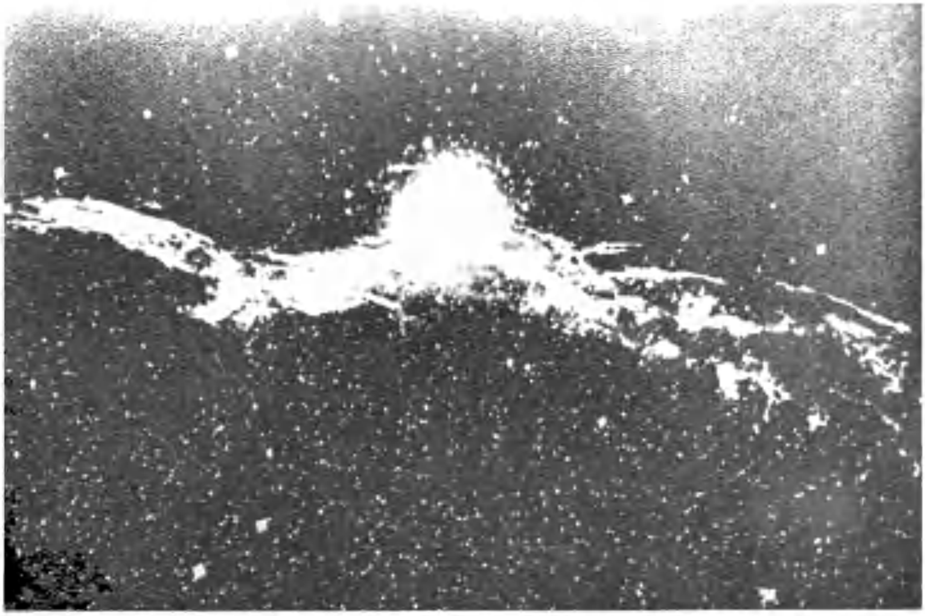


Four consecutive photographs of a gigantic eruption on the Sun.

Photograph of one of the galaxies.

study requires immense and combined efforts of scientists the world over. To give an idea of how much has been done up till now, it will suffice to mention that several hundred thousand galaxies alone have already been investigated and catalogued. However, we must remember that not only galaxies, but separate stars are also studied. Of great importance to science is the study of interstellar matter and gas. One of the photographs shows a gaseous nebula.

Having had a look at the photographs of various objects of astronomic investigations, let us return now to the instrument by means of which they were made—the telescope. We have seen that it enabled scientists to achieve a great deal, but far from all they would like to. Telescopes are anything but ideal or omnipotent. They can be perfected only to a certain limit imposed by the laws of optics and the properties of the Earth's atmosphere. For example, it is impossible to raise the magnification of the telescope above a certain, comparatively small value. And if any of



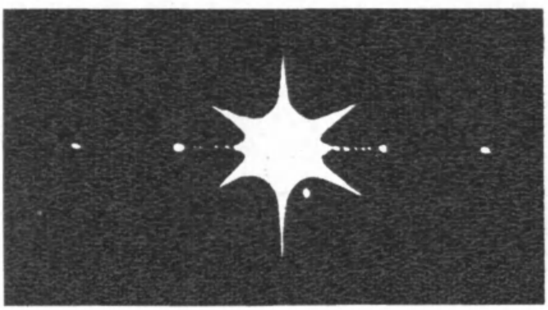
Luminous gas nebula.

our readers imagined that large telescopes are built only to obtain higher magnifications, they were mistaken. The maximum possible magnification does increase with the diameter of the objective; however, the chief aim in building gigantic telescopes is not this, but to increase the quantity of light collected and thus to penetrate deeper into the infinite expanses of the Universe.

The limit of magnification of a telescope is set by diffraction. The smaller the diameter of the objective and the stronger the magnification, the greater the influence of this factor. Practically, the best magnification even with very large instruments does not exceed 800 times. In some cases observers purposely double this figure and even quadruple it, but this does not increase the number of discernable details. It only changes the conditions of observation, making them more convenient for work. The phenomenon of diffraction can be seen very well on the photograph of Sirius. The rays issuing from this star are a result of light diffraction. In reality they do not exist.

The "acuity of vision" of a telescope having a mirror 508 centimetres in diameter is 1,200 times higher than that of the eye. This means that the smallest object whose shape is still definable must have an angular size of not less than 0.05″, which corresponds to a linear size of 50 metres on the Moon's surface and 8 kilometres on the surface of Mars. Smaller objects may also be seen, but their shape will be undefinable: circles, squares, rectangles and any other figures become indistinguishable under such conditions, and all look like blurred spots. As has already been said, the greatest useful magnification of a 508-centimetre reflector is about 1,200 ×, but its field of distinct view is very small, only 0.25° in diameter; it cannot fully accommodate even the Moon.

Another factor that limits the magnification is the luminance of the objects to be observed. Raising the magnification lowers the luminance of the image in the telescope. This is natural—the quantity of photons falling on the eye or on the photographic plate depends only on the brightness of the object, the distance to it and the diameter of the telescope objective, and is independent of the magnification. But with increasing magnification the size of the image grows and, therefore, the same number of photons will be distributed over a greater area. Hence, there will be less photons per grain of emulsion or per retinal light-sensitive



When the magnification is too high diffraction begins to hinder observation of the luminaries. The photograph shows a telescopic image of Sirius; the rays diverging in all directions are due to diffraction.

cell in the eye. Such a reduction in the illumination of the plate or the retina may be inadmissable.*

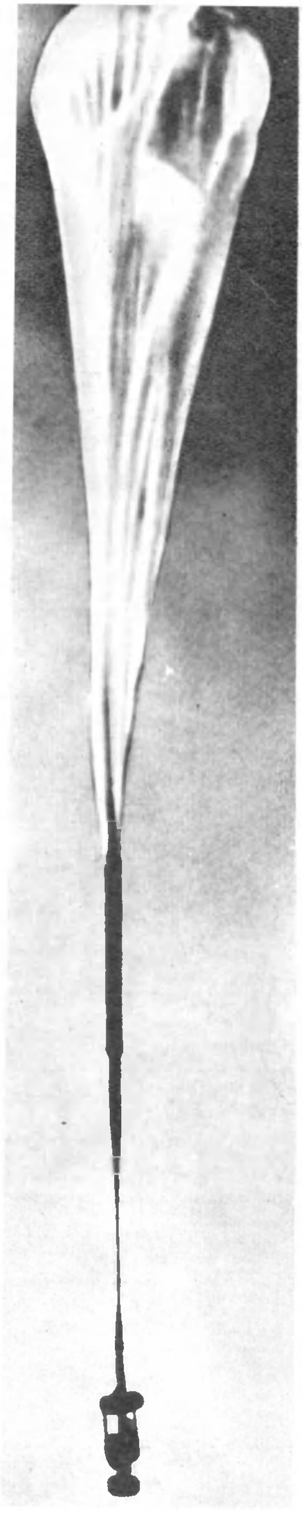
If the first two factors limiting the magnification depended on the telescope diameter, that is, were more or less controllable by man, the third, very substantial factor is of an entirely different nature and quite independent of our will. This factor is the state of the atmosphere.

It appears that our atmosphere is not so transparent and uniform as we are accustomed to think. And this is not by any means due only to the clouds, fog and dust. There are other no less unpleasant obstacles to astronomic observers. What we mean here are the hardly perceptible minute variations in density of the atmosphere, which can usually be seen over heated surfaces: over the asphalt of a highway, over large fields or over prairie lands. If we look through the layer of air above such surfaces, we can see the air streaming and trembling from small currents like a thick syrup being diluted with water.

Such vibrations of the atmosphere, even when they are much less distinct, are dreadful enemies to astronomers. They hinder them in making observations because they cause continuous and non-controllable changes in the sharpness of the images of celestial bodies. Their effect is the stronger, the higher the magnification of the telescope. Raising the latter above a certain value is useless, because

* It must not be forgotten that all this reasoning refers only to the observation of objects of the first category. When observing objects of the second category, which are luminous points, there is no sense talking about magnification. All we can increase with respect to point sources is the distance of their visibility. As we remember, the eye can notice a candle (theoretically) at a distance of 30 kilometres. If a 500-centimetre telescope is used this distance grows to 18,750 kilometres. But then we should see neither the candle nor the shape of the flame. We should see only a luminous point. However, the resolving power is important for second-category objects, too: the higher it is, the easier it is to distinguish individual stars in clusters.

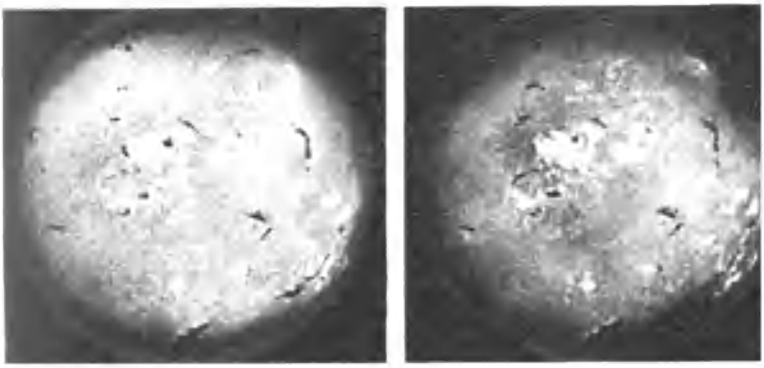
◀ *Two telescopes are installed in the container; a large one for photographing the luminaries, and a small one with a special automaton for pointing the large telescope at a pre-determined luminary (the small telescope is in front).*



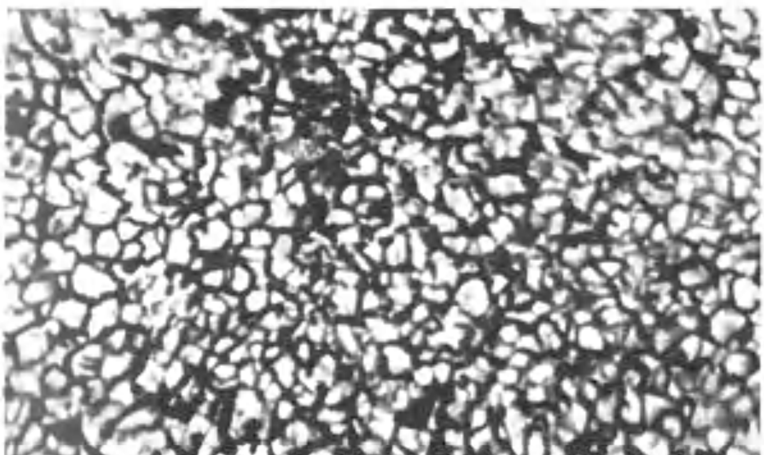
this will only make the image worse. To avoid such obstacles, astronomers go high up into the mountains where the air is not only purer, but much calmer. That is why in the U.S.S.R. the Abastuman and Byurakan Observatories, for instance, were built up in the mountains at 2,000 metres above sea level.

The Earth's atmosphere causes other obstacles too—it is not equally transparent in different regions of the spectrum. At some wave-lengths it absorbs almost all the light. And this property of the atmosphere greatly hinders astronomers in studying the spectra of the Sun and the stars. Until recently astronomers could combat this difficulty only by indirect methods. But a few years ago it was reported that American engineers had found a way of helping scientists: they succeeded in lifting the telescope above the atmosphere. This is done in two ways. The first is to lift a container with the telescope and other equipment in a stratospheric balloon. A balloon of the type shown in the photograph is capable of rising so high that practically the entire atmosphere remains below it. At this altitude (20 kilometres and more) the telescope is pointed automatically at the Sun, and the latter is automatically photographed in different spectral rays, and spectrograms are taken. One of the photographs made from a stratospheric balloon is shown here.

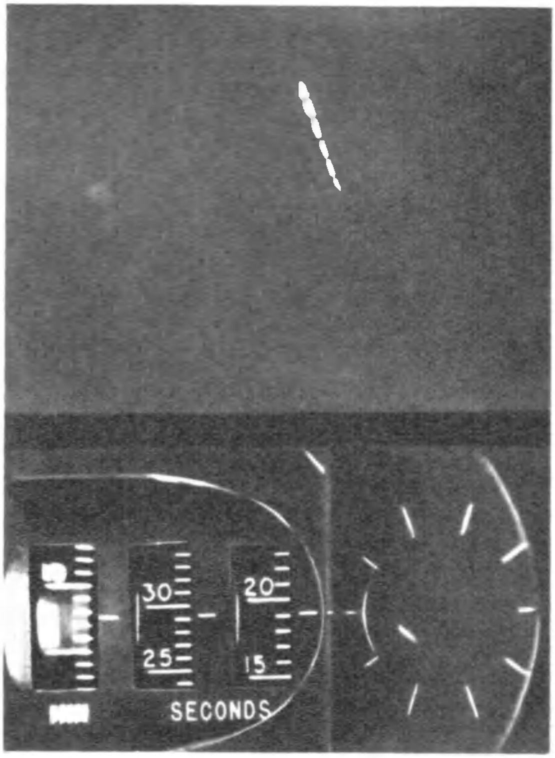
The container with the telescope is lifted above the dense layers of the atmosphere by means of a stratospheric balloon.



These splendid photographs of the Sun were made from a stratospheric balloon.

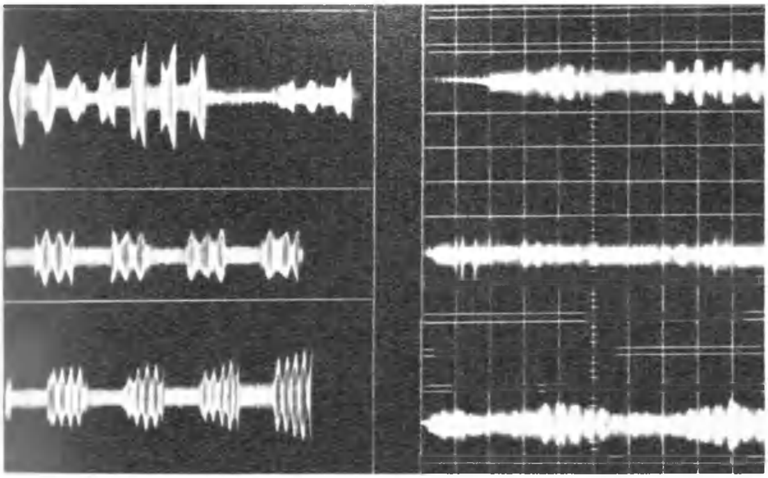


The Sun's surface photographed through a telescope at a large magnification. The telescope was on board a rocket.

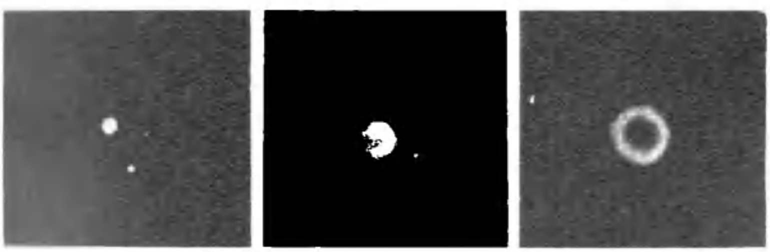


To determine the exact path of a man-made satellite it is photographed in flight by means of special cinema units. The dashed line is the trace of the satellite in the sky. Bottom, left, the dial of a very precise clock is photographed at the same time, making it possible to pin-point the time of flight of the satellite.

The second method is to lift the telescope in a high-altitude rocket. Of course, the telescope in it can be only a very small one. But then, the atmosphere is no longer an obstacle to increasing the magnification. As in the stratospheric balloon photographing and other investigations are carried out automatically. When the rocket returns to the atmosphere the compartment with the installed equipment



This is what the signals of the Earth's first sputnik, its famous "beep-beep", looked like on the screen of an oscillograph.



Consecutive photographs of an artificial comet, a sodium cloud let out into space by the automatic interplanetary station which photographed the Moon.

is recovered by means of a parachute. You can also see photographs of the Sun here taken from on board an altitude rocket.

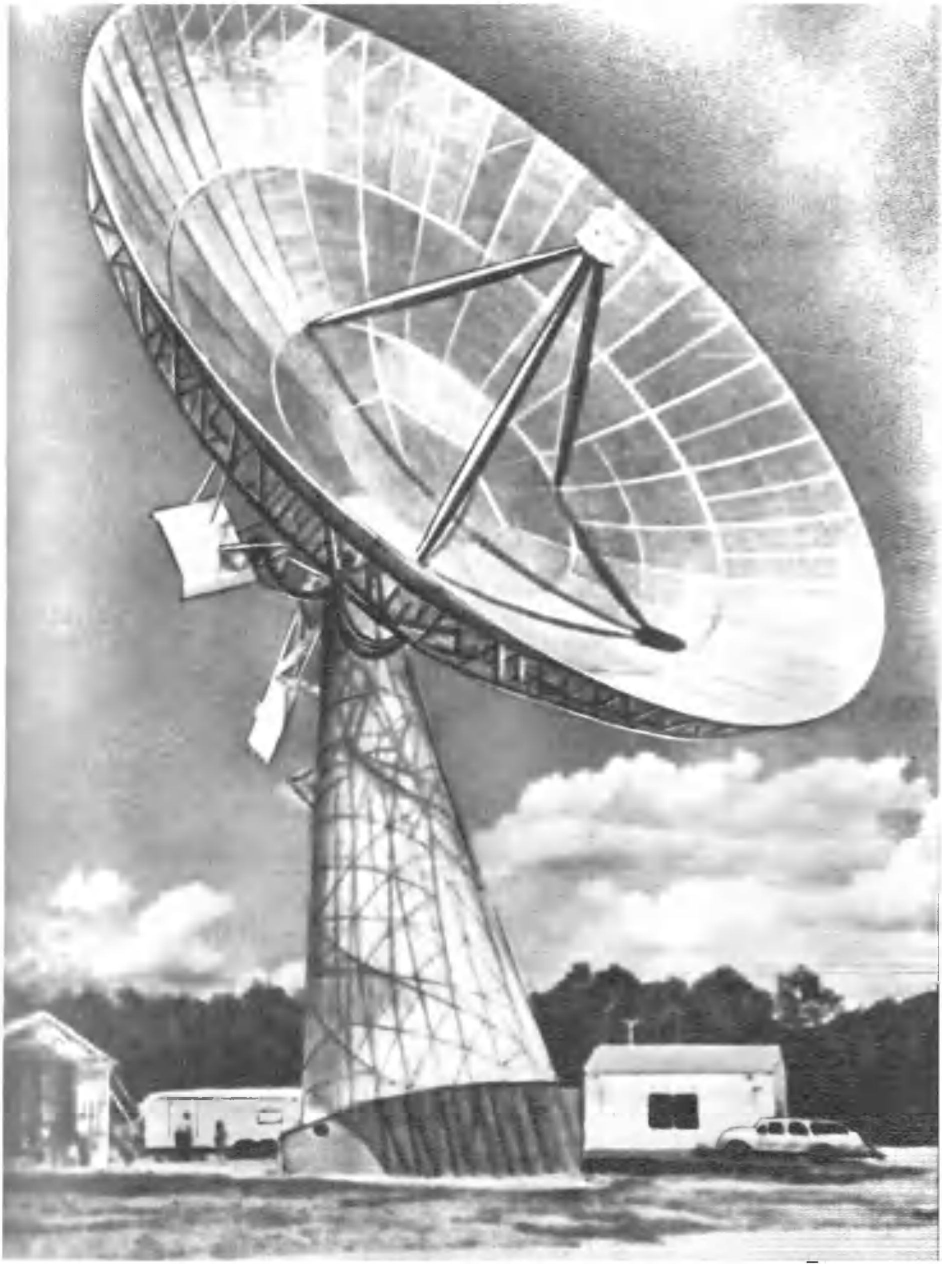
Rocket studies of the upper layers of the atmosphere and of solar irradiations have been carried on for a fairly long time. As is known, meteorological and geophysical rockets were employed by science several years before the first man-made satellite was launched.

Rocket techniques enabled Soviet scientists to make valuable observations of the total solar eclipse of February 15. 1961. On that day a geophysical rocket was launched with a high-altitude automatic station on board. After emerging from the dense layers of the atmosphere the automatic station separated away from the rocket and carried on observations for 210 seconds. This comparatively short time of operation was limited by the short duration of the total eclipse phase.

The station was oriented automatically, and the telescopes, cameras, spectrographs and other instruments carried out the required measurements. The instrument readings were telemetered to Earth, and unique photographs were brought back by the station which landed safely after completing the observation programme.

Modern engineering has furnished astronomers with yet another powerful instrument for investigating the Universe. We know already that there is no fundamental difference between radio and light waves. The only difference is that the longest light waves are much shorter than the shortest radio waves. Hence, it should be possible to devise a unit based on radio waves resembling the telescope in designation. Instead of light waves, such a unit would receive the radio waves radiated by celestial bodies. This unit was called a "radio telescope" by analogy with the telescope.

Nor is this analogy just superficial. There is very much in common between optical and radio telescopes. Indeed, the radio telescope greatly resembles the reflecting telescope. Like the reflector, the radio telescope uses a parabolic converging mirror. True, it differs from optical mirrors. Its surface is made of metal sheets or even metal screen. It is not much of a mirror for light waves, but radio waves are reflected very well not only by metal sheets, but by

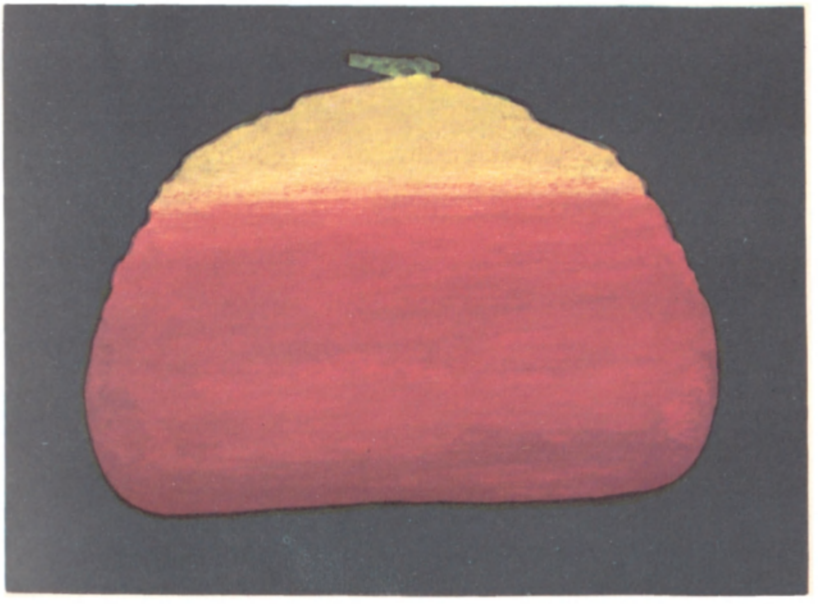


This radio telescope is a comparatively small one; its aerial is only 25 metres in diameter.

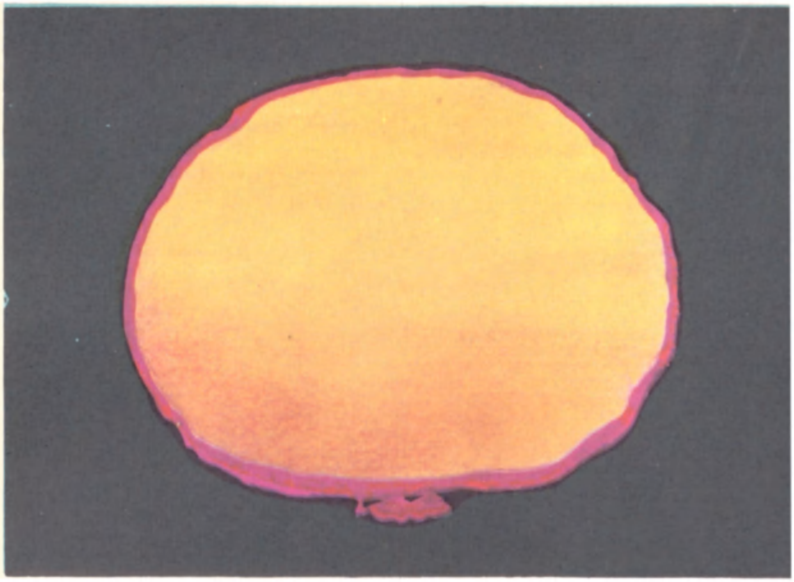
Radio telescope at Jodrell Bank, England. The diameter of its parabolic mirror is 76 metres.

metal screens also, provided the side of each of its apertures is shorter than the shortest of the radio waves to be received.

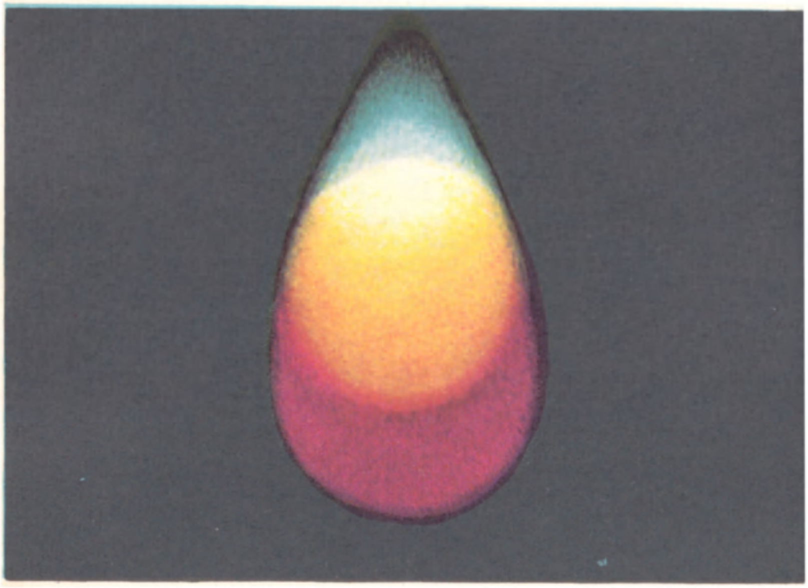
Screens are used in parabolic mirrors for radio waves to lighten the mirror and to decrease the pressure of the wind on it. This may seem strange at first glance, but it will become quite clear as soon as we state the size of the mirror. It is very large. The mirror diameter of an average radio telescope is about 20 or 25 metres while the largest in existence has a mirror 76 metres in diameter, that is, 15 times as large as that of the largest optical telescope.



To see what is shown in the first of these three colour photographs, Jules Verne's heroes journeyed all round the world. But this is not at all necessary, any attentive observer can see the green ray without going very far away from home. It can often be seen at sunset, especially above the sea.



Besides the green ray, a red ray appears sometimes as well; here is a photograph of this ray. Probably, everybody has seen the bright scintillating planet Venus with its play of pure colours.



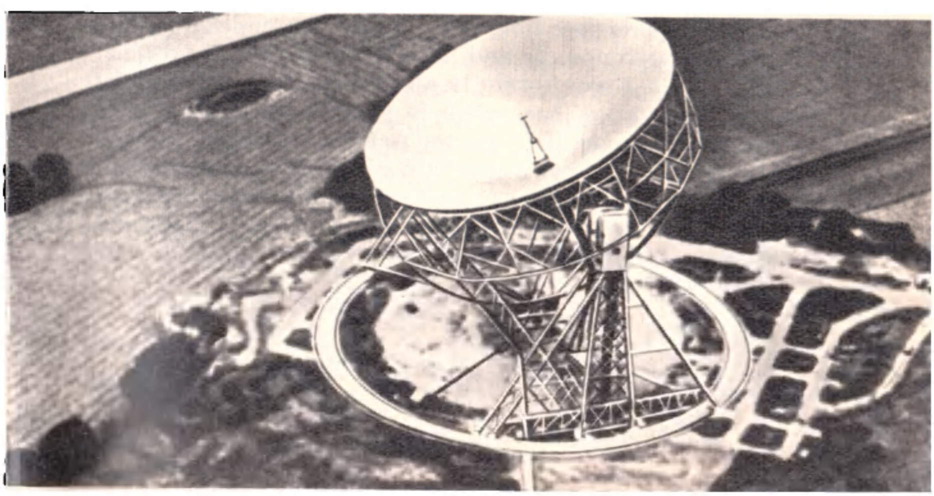
The third photograph shows what Venus looks like at sunset and the play of colours in the telescope.

The mirrors of radio telescopes are made so large for the same reason as in optical ones—to collect as much energy of radio radiations as possible and to focus it. A comparatively small antenna is set up at the focus of the parabolic mirror. Its purpose is to convert the energy of the electromagnetic waves proportionally into electrical voltage and current.

In optical systems the receiver of light energy is the eye, a photographic plate, a photoelectric cell or certain other types of light receivers. These receivers are of no use in radio telescopes. Their place is taken by a supersensitive radio receiver, to which the electrical voltage of a radio frequency is fed from the antenna. But this is not the only difference between optical and radio telescopes. Another important difference is that radio telescopes do not give images in the sense we are accustomed to. All the energy of the radio waves is concentrated in a very small volume—in the focus of the mirror. Here it is captured by the antenna and practically wholly passed on to the receiver.

The resolving power of radio telescopes is much lower than in optical telescopes, despite the large size of the mirror. This, it appears, is due to the fact that the ratio of the mirror diameter to the wave-length is many times smaller in radio telescopes than in optical ones. For example, when operating on a wave-length of 21 centimetres a radio telescope with a mirror 180 metres in diameter (such a telescope was to have been built in the U.S.A., but the idea was abandoned) would be able to distinguish two

Bird's eye view of the Jodrell Bank radio telescope.



Accumulation of hydrogen clouds in our Galaxy. Cross indicates centre of Galaxy.

sources of radiation on the Moon, only if they were no less than 480 kilometres apart. An optical telescope with a 5-metre mirror can distinguish two light sources on the Moon even if they are only 50 metres apart.

Radio telescopes have considerably extended the possibilities of astronomers and have enabled them to discover much of what was formerly absolutely inaccessible. Thus, radio observation has made it possible to penetrate the atmospheric cover of Venus and to measure the temperature of its surface. Jupiter is now being investigated in a similar way. Of no less interest to science are the radio radiations of the Sun, the stars and galaxies. One very interesting discovery made with a radio telescope is that of a radio

galaxy in the constellation Swan. Radio waves travel from it to Earth 650 million years. But despite this incredibly large distance the radio radiations of this galaxy are comparable in power to those of the Sun. Formerly, astronomers had not known of the existence of such a galaxy because it is almost invisible in ordinary telescopes. And only after radio telescopes had indicated where to look for it, a photograph was made on which this galaxy came out very faint, because its light radiation is very low. But its radio radiation is intense, and that is why it is called a radio galaxy. Scientists believe it is an "exploded" stellar system. Radio telescopes have also made it possible to investigate accumulations of interstellar matter. In one of the photographs given here you can see the distribution pattern of immense hydrogen clouds in our galaxy.

Microscopes

A grammophone or magnetic tape record can be played only in one direction. If we run them backwards quite unmusical sounds result. Two of the greatest geniuses, Bach and Mozart, it is true, composed several pieces that sound exactly the same whether played forwards or backwards. But these are nothing but curios, exceptions which confirm the rule.

And even not the rule, but the law. The law, in accordance with which our world is asymmetrical in time. We can put a piece of metal stock in a lathe and machine it to the shape we need. But there is no machine, there are no means by which we could restore the machined pieces and the cuttings back into the same stock we started with.

There are laws of another kind. Of course, they do not upset the relationship between cause and effect because they operate in a different sphere. On the basis of these laws devices can be built in which certain processes may be reversible. For instance, some types of electrical machines can serve as sources of electric power if their rotors are rotated by means of engines, but can also be motors themselves if connected to a source of electric power. Such machines are referred to as reversible.

Reversible devices are known in optics too. One of these

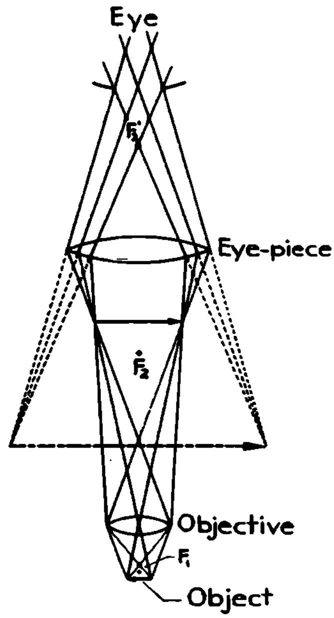
is the converging lens. A beam of parallel rays passed through it converges at one point, called the focus. On the other hand, a beam of light diverging from a point source of light situated in the focus changes into a beam of parallel rays after passing through the lens. True, in this case reversibility has a slightly different meaning, because it refers to the path of the rays and not to a process.

A similar thing takes place in other optical devices. If we focus a photographic camera on a plane picture, we get its image on the focussing screen. But if we put a transparency with the image of the picture in place of the focussing screen and hang a screen in place of the picture, our camera becomes a projector and we shall see a picture on the screen, painted by the light passing through the transparency and the camera lens.

The optical system of a microscope does not differ from that of the Kepler telescope. The only fundamental difference is that in the microscope the light travels the opposite way. The long-focus objective of the telescope becomes the eye-piece, and the telescope eye-piece becomes the short-focus object glass of the microscope.

The first time you look through such an inverted telescope you will probably disagree with what was just said, because all objects will be diminished in size and will seem farther away. But do not let this daunt you. To get a magnified image all you have to do is bring the object to a distance of less than two, but a little more than one focal length from the object glass. Those who have succeeded in making themselves a telescope according to the instructions given earlier in the book, can easily verify this. Then they will see that they have made a microscope as well.

Thus, the same optical system can be used as a telescope or as a microscope. The difference is that in the first case the object is at a distance exceeding the focal length of the long-focus lens by an immense number of times; in the second, it is at a very short distance (between one and two focal lengths) from the short-focus lens. Hence one more difference: the image seen in the telescope is far smaller than distant objects (a telescope may even magnify very close objects), while a microscope image is always larger than the object observed.



Optical system and paths of rays in a microscope.

It must not be thought, however, that even the best telescope can simultaneously be a very good microscope and vice versa. This is not so, of course. In practice, the design and optical parts of telescopes and microscopes differ greatly in execution, because in each case they are calculated to give the best performance for their particular application. And the applications of these instruments are entirely different.

The optics of different microscopes also differ widely, though the system is always the same. These differences are also due to the dissimilarity of the spheres in which the microscopes are employed. Of course, there are general-purpose instruments which can be used in widely differing conditions. But such microscopes do not always give the best results. Often a very simple, but specially designed microscope is more useful for definite observations.

Telescopes are at present made according to three optical systems. Microscopes are made practically according to one, namely, according to the system of an inverted Keplerian telescope. Hence, they are all refractors. Reflecting microscopes could also be made. Even Newton had intended to fashion such a microscope, but for some reason or other did not put his idea into practice. Nor were reflecting microscopes made in subsequent years, because they offered no advantages compared to lens-type microscopes. Only in our time were several reflecting microscopes made specially for work in the short ultraviolet range. But these microscopes did not find wide application because they were supplanted very soon by the electron microscope which appeared almost at the same time.

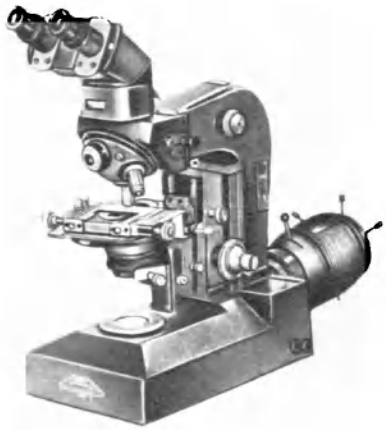
Astronomy existed as a science long before the telescope was invented. The telescope enabled scientists to extend immeasurably their knowledge of the Universe. The microscope did much more—it made possible the discovery of a world, the existence of which nobody had suspected. And this discovery brought to life a large number of very important sciences.

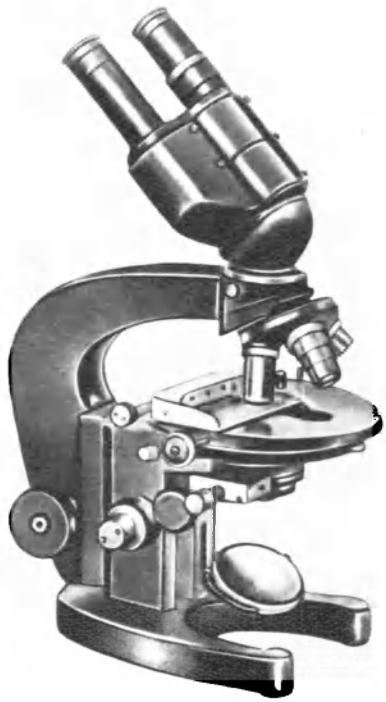
The first microscopes were as imperfect as the first telescopes, but they very soon began to improve. The famous Dutchman Anton Leeuwenhoek (1632–1723), the first microbiologist in history, was not a professional scientist. But it was he who made very good microscopes for that time (about 1677) with magnifications of up to 300×. With their aid he first observed the movement of the blood through capillaries, red blood corpuscles, the structure of muscles and the crystalline lens of the eye; he discovered and studied many micro-organisms.

Years went by, and many opticians worked to perfect the microscope. Its quality became better and better. Scientists succeeded in eliminating the colouration of images, practically did away with shape distortion, considerably increased the magnification and resolving power, that is, the definition of minute details of images. The same years also saw the field of application of the microscope greatly extended. It was found to be indispensable not only in microbiology, but in a multitude of other fields as well. In our days the microscope is to be found on the work

desk of the biologist and the physician, the chemist and the physicist, the geologist and the metallurgist, the archeologist and the criminalist, etc., etc. No less firm is the stand microscopes have taken in industry. Various industrial processes and inspection operations in the manufacture of high-precision responsible machine elements, radio tube components, transistors are effected with the aid of microscopes. They are often used in combination with photographic and even cinema cameras.

Modern microscopes are very precise and highly efficient optical instruments. There is a great variety of types and designs depending on the field in which they are to be used. The microscopes most usually seen, and probably the most commonly used, are those of the types shown in the first photograph. These are known as biological microscopes, though they can, of course, be employed in all other fields where the design of the illuminator and stage permit. The next photograph shows a microscope of the kind employed at industrial plants for inspection and measuring. Note the design of the stage: the two micrometer screws for shifting the stage in two directions at right angles, and the vernier



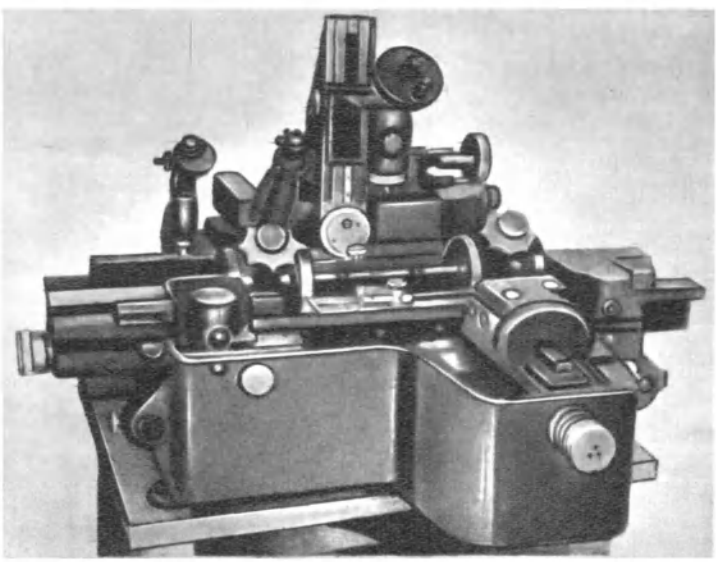


Modern universal microscopes.

goniometer by means of which the angle of rotation of the stage can be read off with great precision.

Another type of microscope employed in industry is the measuring projecting microscope. By means of this microscope the images (mostly the profile images) of various minute parts can be projected on to a circular screen. The size of the image can be from 5 to 100 times as large as the original. Such microscopes are used to check the accuracy of execution of precision thread profiles, miniature punched parts and so on. Many measuring instruments designed to measure sizes to 0.001 millimetre and less include a microscope as one of their design elements.

Thus, the modern microscope has been developed to a high degree of perfection. But, like the telescope, its possibilities are not unlimited. Moreover, they are already now almost completely exhausted. And we can hardly expect any radical improvements in optical microscopes in the



A modern industrial microscope.

A projecting microscope.

future, for their possibilities are limited by the very properties of light.

One of the factors limiting the useful magnification in telescopes is the atmosphere. This factor is of no importance to users of the microscope. On the other hand, here diffraction plays a greater role than in the telescope. As we know, diffraction can be combatted in telescopes by increasing the diameter of the objective. In principle, the effect can be diminished to any desired degree. But in practice this is hampered by the immense technical difficulties encountered in making large-diameter lenses. However, these difficulties are not inherently insurmountable. What engineering has not succeeded in coping with in the past, is now accomplished with comparative ease and, therefore, it may be expected that in the future engineering will find a means of increasing the size of telescope lenses still more, if necessary.

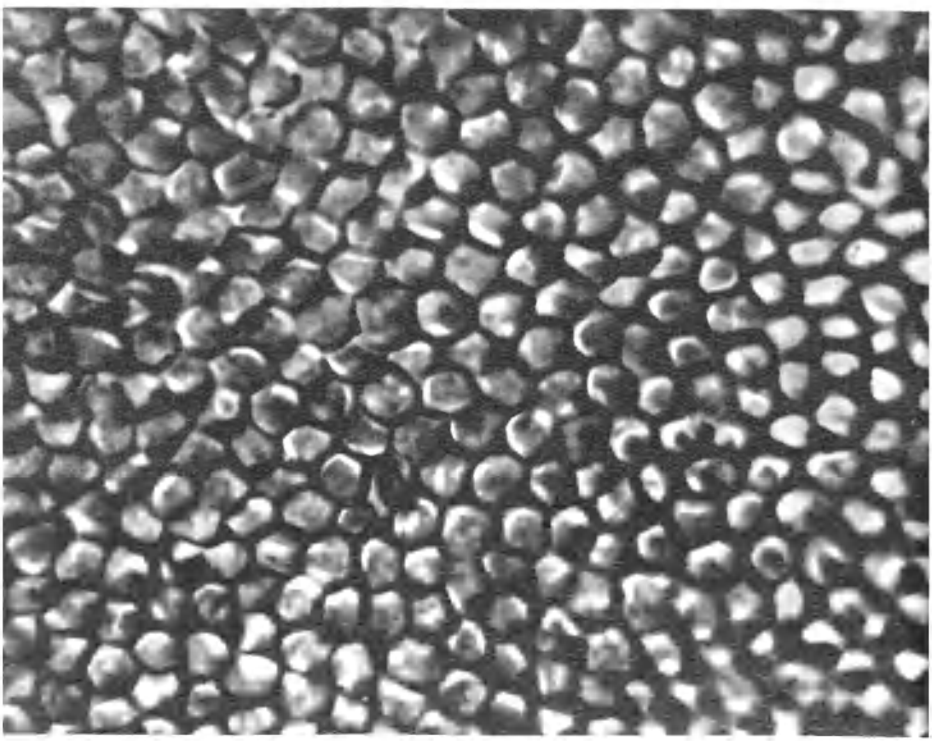
As to the observation of microscopic objects, here elimination of diffraction phenomena is inherently impossible. They can only be reduced. In this case, the effect of diffraction cannot be diminished indefinitely by increasing the lens diameter.

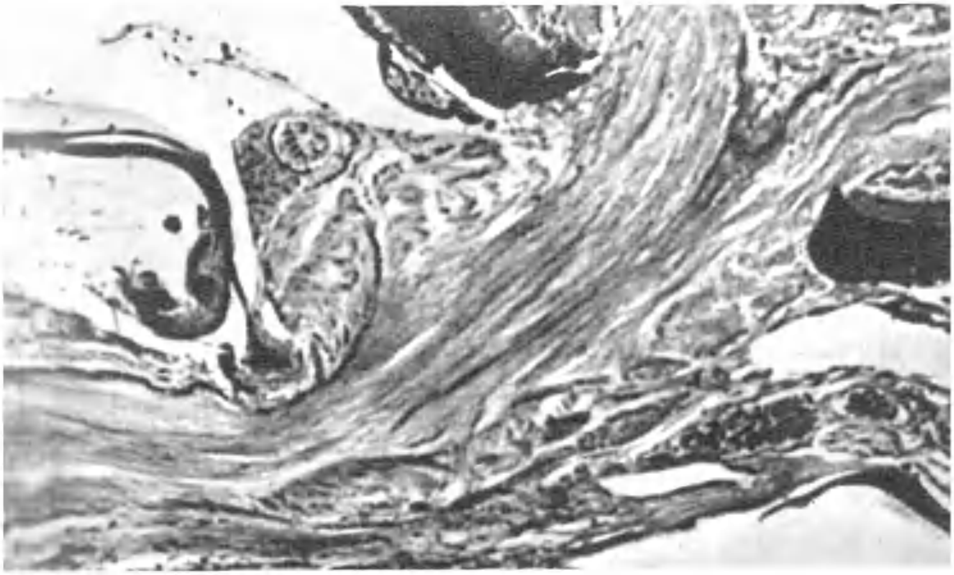
The second method of combatting diffraction phenomena, the possibilities of which are also limited, is by immersing the microscope objective in a transparent medium with a high coefficient of refraction. Water and cedar oil are used for this purpose. Microscopes whose objectives are immersed in a strongly refracting medium are referred to as immersion microscopes.

By taking advantage of all the available methods of combatting diffraction, microscopes can be made (and have been made already) through which objects can be observed having a linear size of not under 0.3 λ, λ being the wavelength of the light in which the object is examined.

Our eye is stimulated by light waves from 380 to 770 millimicrons long. If we illuminate the object with the

Photograph of the retina of the human eye obtained with the aid of a microscope.





The microscope has also helped to study the structure of the trunk of the optical nerve. This photograph shows the optical nerve of a fish; even separate fibres can be discerned.

shortest violet rays we can distinguish the shape of objects having a linear size of not less than 125 millimicrons. Usually white light is used in microscopes rather than monochromatic. Therefore, to assess the effect of diffraction a certain average wave-length is assumed and the resolving power is considered to be about 200 millimicrons or 2×10^{-5} centimetre. This is the limit size of the smallest microscopic object that can just be discriminated. Unfortunately, it is still about 2,000 times greater than the size of a molecule, and hence, the latter will never be seen with an optical microscope.

It is also worth mentioning that particles even 5 millimicrons in size can also be seen under the microscope. Ultramicroscopes are usually employed for this purpose. This microscope differs from the conventional type only in the design of its illuminator, which illuminates the particles sideways. Under such illumination the particles appear like bright points on a dark background. But the image we get this way gives no idea of their shape. However, such

observations are also often very valuable. As a matter of fact, our observations of the stars are no better than this.

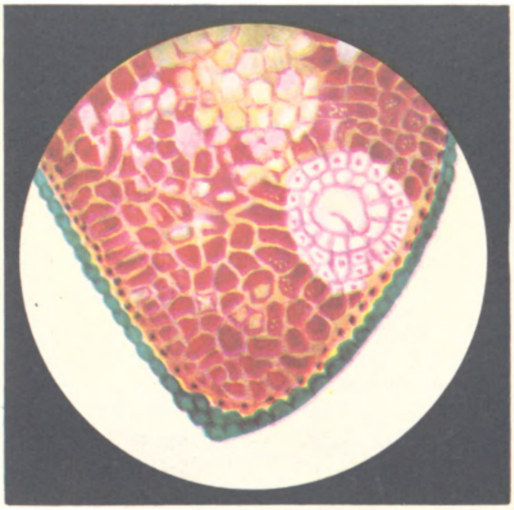
Owing to diffraction the magnification of microscopes is comparatively small. Rather, it can be made considerable by selecting a suitable object lens. But in most cases this is useless. At very high magnifications the amount of discriminable details does not grow, but the image becomes more and more blighted by diffraction patterns. And even experienced microscope operators not infrequently mistake them for the image of minute details of the object.

Here is what G. Slyusarev writes about this in his book "The Possible and the Impossible in Optics":

"...the useful magnification of a microscope does not exceed 300 to 500×. Like in telescopic systems, we can double and treble these figures. Still, magnifications above 1,000× are clearly useless and even harmful: the diffraction patterns come out distinctly in such images, distorting the outlines of the objects observed and lead to all kinds of errors and confusion.

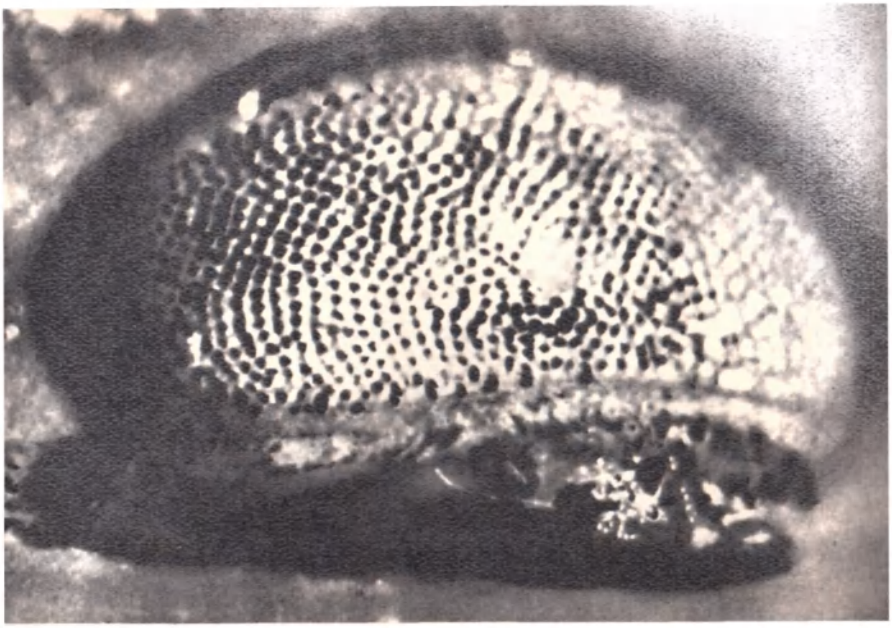
"In general, insufficient knowledge of optics is often the cause of mistakes, and sometimes very big ones, not only on the part of young, inexperienced workers, but even of world-famous scientists. A number of objects of great interest to biology, zoology, cytology (the science of the cell), have sizes just beyond the resolving power of the microscope. With skilful use of the microscope these objects can be detected, but obviously, one is very apt to fall under an optical illusion in this case. This has happened before and will go on happening until microscope users realize that it is just as difficult to examine images through the eye-piece of a microscope without knowing the theory of the latter as it is to read a book in an unknown language."

One of the methods of increasing the resolving power of the microscope, and hence, its greatest possible magnification, is to decrease the wave-length of the light in which the object is viewed. The first obstacle to shortening the wave-length is the insensitivity of our eye to ultraviolet radiations. By substituting a photographic plate for the eye we can move considerably into the region of ultraviolet rays and thus raise the resolving power and the useful magnification of the microscope. Major achievements



Colour photomicrograph obtained in ultraviolet rays.

Aerial colour photography makes it possible to detect mineral deposits by the colour of the Earth's surface and the colour of its vegetative cover.

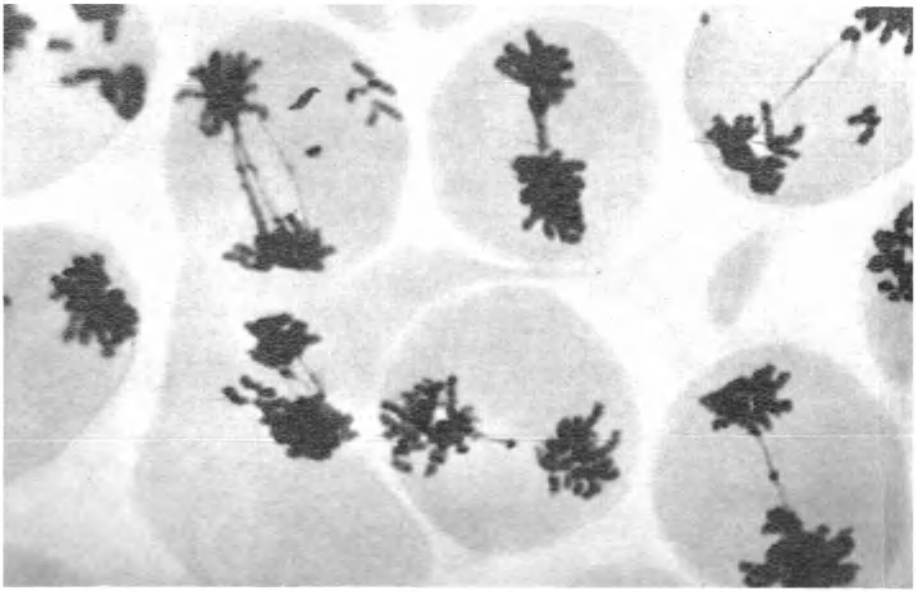


Crab's eye, greatly enlarged. It resembles the eye of an insect, particularly, that of a dragon fly, and is called a facetted eye.

in the construction of ultraviolet microscopes have been made by the Soviet scientist Y. Brumberg.

Such microscopes are employed fairly often by scientists, but they have one bad disadvantage: the object under investigation can be seen only after the photograph is developed. For this reason another important device is now added to the ultraviolet microscope—an image converter, which converts the invisible ultraviolet image into a visible one. Converters of this type are based on the well-known phenomenon of photoeffect.

But let us return for a while to the very interesting method of ultraviolet colour photography of microscopic objects. Essentially, no natural colours are involved in this method. But very often, to improve the definition of minute details and to determine the optical properties of its separate parts, the object is photographed in various rays of the ultraviolet spectrum. The longest-waved of these may conventionally be called red, intermediate—green, and the



This is what cells look like through a microscope.

shortest—blue. Three negatives obtained in this way can be used to make a colour print. An image of this kind may show much more detail: the red areas on it correspond to the parts of the object that gave off a lot of long-wave ultraviolet rays, the green areas, to the parts that gave off a lot of intermediate-frequency rays, etc. Knowing the laws of colour mixture, you can judge the composition of the rays incident on the parts of the image where the colours differ from the primaries. A photograph of this kind is reproduced here.

Ultraviolet microscopes have a resolving power and a useful magnification of up to twice that of ordinary optical microscopes. Unfortunately, it is difficult to continue shortening the light waves still further, because most objects greatly absorb short ultraviolet rays. Besides, difficulties of another kind arise. These are related to the optical properties of glass, namely, the absorption of ultraviolet rays by the latter.

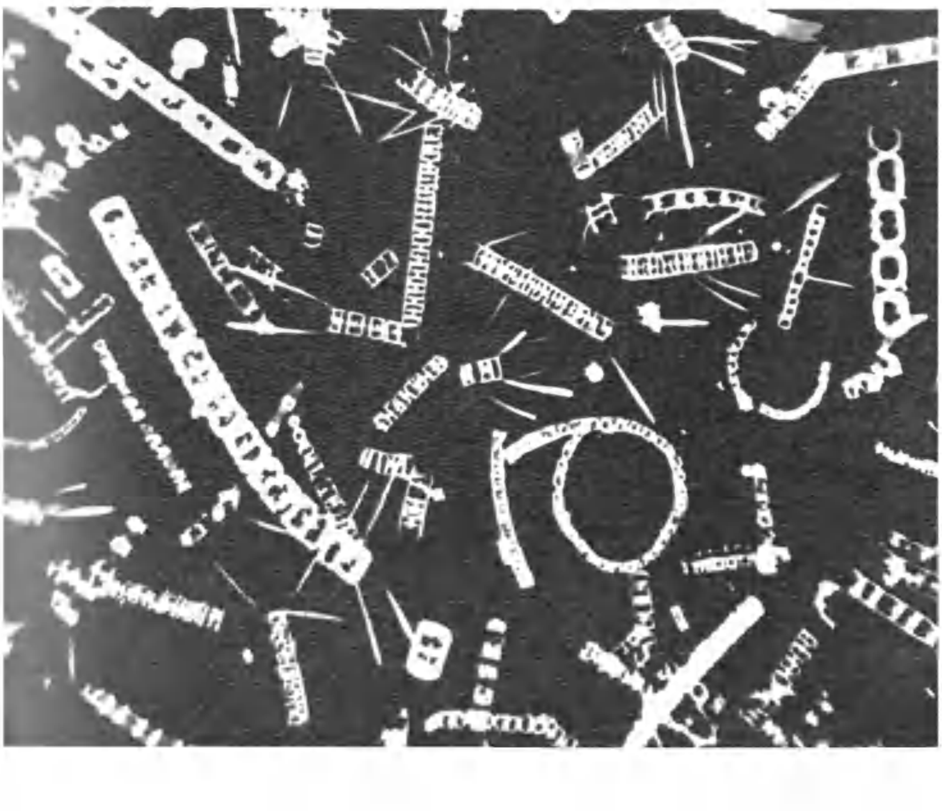
In recent years wide use has been made of another part of the range of invisible light rays, the infrared region.

Naturally, when working in these rays, the resolving power and useful magnification of the microscope are lower, but the purpose of using infrared rays in microscopy is not this; these rays make possible investigations which hitherto seemed quite impossible. It was found that many organic and inorganic substances which are opaque to the visible light rays, transmit infrared rays quite readily. This enables investigation of their microscopic structure with the aid of special infrared microscopes.

A model of an infrared microscope was built by the Laboratory of Electrical Physics of the Institute of Metallurgy of the U.S.S.R. Academy of Sciences in 1956–1957. This model (МИК-1) proved to be a good one and has been in serial production since 1960.

Microscopes of this type can be used for observation both in visible light and in the near infrared (up to 1,200 millimicrons). Observations can be made in reflected and in transmitted light. The microscope is equipped with a con-

These are not precious bracelets and necklaces. What you see is a photomicrograph of minute aqueous organisms called plankton.



verter, so that the image can be observed directly or photographed at will.

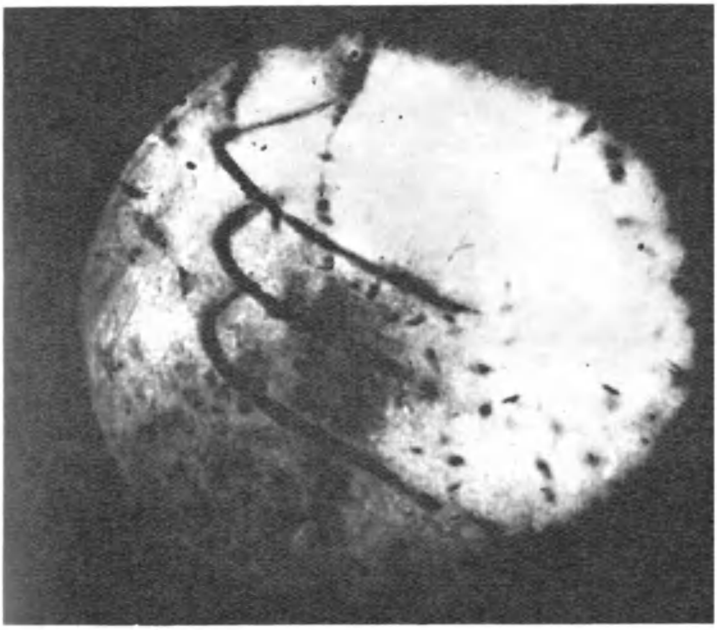
We are accustomed to consider metals opaque, and indeed, we have never seen them otherwise. And if a piece of pure silicon or pure germanium were to come into our possession, it would never occur to us while looking at the silvery lumps of these metal-like substances that they are transparent. Actually, however, they transmit light very well—not visible, but infrared light.

Nowadays silicon and germanium are the materials of modern radio electronics. The crystals of these chemical elements are used to make many semi-conductor devices: diodes, photodiodes, transistors, phototransistors, solar batteries for man-made satellites, elements of refrigerator units. When destined for these uses silicon and germanium must be completely free from impurities, and must have no defects in their crystals. The preparation of chemically pure large-size crystals is one of the most complicated problems ever solved by metallurgists. And it is therefore not by accident that the infrared microscope was invented not in an optical institute, but in the Institute of Metallurgy, where it was most needed.

The infrared microscope makes it possible to see the inside of silicon and germanium crystals. It enables more profound investigation of the defects that arise and thus make it easier to find ways of eliminating them. The photograph presented here, made with a "МИК-1" microscope, shows a silicon crystal; the dark bent lines are defects in its structure.

Thus, infrared rays have made it possible to penetrate into the depths of substances which are opaque to ordinary light. But this occurred at the expense of a lowering of the resolving power and magnification of the microscope. Evidently, most of our readers are therefore wondering why x-rays or gamma-rays, which pass through practically all substances and at the same time have very short wavelengths, were not used for this purpose.

This is quite a legitimate question. Indeed, a microscope operating on these rays would have a very high resolving power. With its aid even molecules could be seen. Scientists have attempted to design x-ray microscopes. And they



Photograph of a defect in a silicon crystal, obtained in infrared rays with the aid of a "МИК-1" microscope. Courtesy of the Institute of Metallurgy of the U.S.S.R. Academy of Sciences.

exist already. But so far no instruments have been designed which can compare in quality with conventional microscopes.

The trouble is that science knows of no material which could refract x-rays or gamma-rays like glass refracts ordinary light rays. There have been attempts to employ reflector systems instead of lenses, but not much was achieved along these lines. A mirror, which reflects visible and even ultraviolet rays very well, is not a smooth reflecting surface to x-rays, but one cut up with deep furrows and holes. This is due to the fact that surface irregularities which are imperceptible to the rather long waves of visible light are commensurable with and even larger than the wave-lengths of x- and gamma-rays. For this reason mirrors for such

short-wave rays require extraordinarily fine polishing, which is impracticable for various reasons. But this is not the only difficulty. It is no less important that x-rays can be reflected by mirrors only if their angles of incidence are small. When the angle of incidence is sufficiently steep, reflection will not occur even from a good mirror, because the rays penetrate into the bulk of the latter.

Still, we owe it to roentgen rays that we have been able to get an idea of the structure of the molecules of various chemical compounds. Only this was achieved not with the aid of microscopes of any kind, but by other means —by taking advantage of diffraction phenomena. The same phenomena which are justly considered the bitterest enemies of all microscope operators, and prevent us from seeing not only molecules under the microscope, but much larger objects as well.

But in x-ray investigations of the structure of substance diffraction has done a great deal of good. Investigation of the diffraction patterns of crystals has enabled scientists to find methods of determining the structure of substance by these patterns.

The example of diffraction suggests a very important thought. There are no absolutely harmful nor absolutely useful phenomena in nature. Each of them has its good and bad sides. We all know that the friction in the wheel axles of railway cars makes the engine spend a great deal of extra power even on horizontal sections of the railway. And that is why we do everything in our power to reduce it to a minimum. But at the same time, if there were no friction at all, the engine would not be able to move, because its wheels would merely skid round and round on the spot.

It is almost always pointless to talk about what would happen if any of the laws of physics were to change or disappear altogether. Physical laws do not depend on the will of man. But the utilization of these laws in a way to make them useful does depend on the will of man, on his power of thinking. And whenever a law comes up before man as an insurmountable obstacle he invariably, by the force of his mind, finds a solution to the problem on the basis of that same, or some other, physical law.

We know already that it is precisely the laws of light that prevent us from raising the resolving power and magnification of optical microscopes. Everything, or almost everything possible at the present-day level of science has been done in this direction. But is there no other way, are there no other phenomena which could help us do what light prevents us from doing? We can answer this question ourselves. For this we need only recall what is known to science about the nature of light. Light, it says, possesses the properties of both waves and particles.

But is there no other physical object that has similar properties? There is. And we know which. The electron exhibits the same combination of corpuscular and wave properties.

But if this is so, could we not design a microscope employing the waves associated with electrons instead of light waves?

We could. And we should, because the wave-length associated with electrons can be made exceedingly small, even smaller than that of x-rays. Hence, the resolving power of such an electron microscope may turn out to be very high.

The idea of the electron microscope probably arose soon after Louis de Broglie's discovery in 1924. He then forecast that electrons must possess wave properties. And a short time later this was confirmed by experiment: scientists discovered the phenomenon of electron diffraction.

However, it was a long way from the idea of the electron microscope to its practical embodiment. Scientists first had to create the second indispensible component of the electron microscope, its lenses. Ordinary lenses are of no use for refracting electron beams. Fortunately, this problem proved more simple than in the case of x-rays, for in contrast to electromagnetic waves, electron beams can be deflected in electric and magnetic fields.

Development of the theory and the practical embodiment of various electron-optical systems took quite a long time, so that the first more or less satisfactory electron microscopes came into existence only towards the beginning of World War II. In them, light rays were substituted by electron beams, and glass lenses by systems of electro-

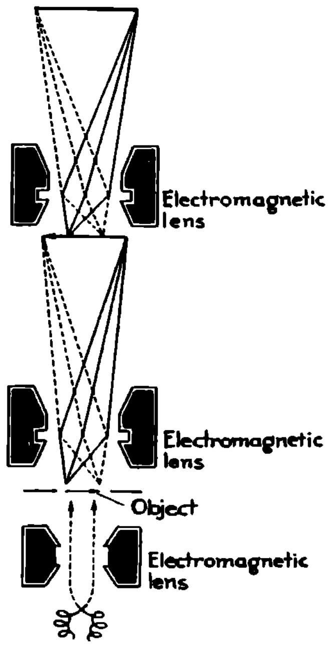


Diagram of an electron microscope. In principle its system does not differ from that of an optical microscope, but in this case the part of the lenses is played by electromagnetic coils.

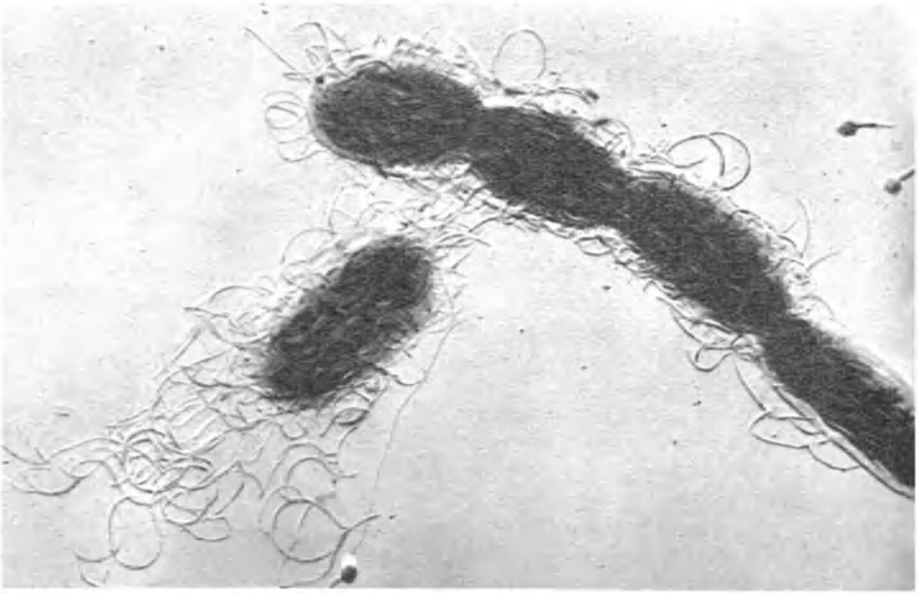
magnetic coils and electrodes connected to sources of electricity. But the paths of the electron rays in the electron-optical system of this microscope remained the same as in the optical microscope.

Of course the design of the new type of microscope is entirely different. The electron microscope is much more complicated and much larger than the optical microscope. This is due, primarily, to the fact that the electron beam can travel freely only in a vacuum. For this reason a very high vacuum is maintained in the tube of the electron microscope. Light cannot help moving, but electrons have to be accelerated. For this purpose the electron microscope

is furnished with a special accelerating system fed by a high-voltage source. For example, in the "УЭМ-100" electron microscope this voltage is as high as 100 thousand volts. The wave-length associated with an electron at such an accelerating voltage is only 0.039 Ångstrom units, or 3.9×10^{-10} centimetre.

If the resolving power of the electron microscope were limited only by diffraction, we could see even molecules. Unfortunately, the resolving power is lowered to a considerable extent by the very lenses of the microscope. Their quality is incomparably worse than that of optical lenses, and so far no way of eliminating this shortcoming has been found. That is why the resolving power of modern electron microscopes is still far from the theoretically possible limit and amounts only to a few Ångstroms. But even this value

Negative image of a tomato leaf cell affected by the tobacco mosaic virus. Courtesy of the Laboratory of Electron Microscopy of the U.S.S.R. Academy of Sciences.



Bacteria and phage particles. Courtesy of the Laboratory of Electron Microscopy of the U.S.S.R. Academy of Sciences.

exceeds the resolving power of optical microscopes by several hundred times. Besides, in addition to the usual observations, diffraction studies can be carried out in some types of electron microscopes. The diffraction patterns obtained in this way, called electronograms, enable scientists to study the structure of crystals and molecules, which cannot be done by other observation methods.

The magnification of present-day electron microscopes runs into the tens of thousands. It is the product of two values—the electron-optical magnification and the photographic magnification. In the "УЭМ-100" electron microscope the image is photographed on a 6×9 cm plate. This image can be additionally magnified when printing. A total magnification of 50,000× or 75,000× is not the limit.

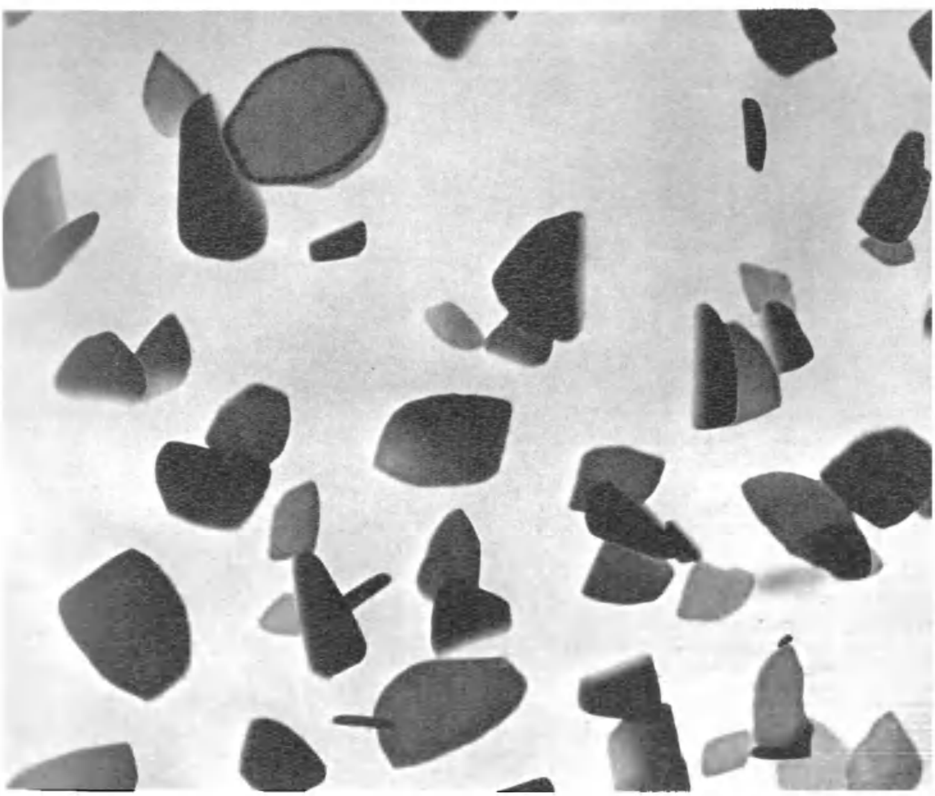
Such a magnification is a very large one. To give you a better idea of how large it is, it will be relevant to say a few words about the preparation of sections for investigation under the electron microscope. This is a very delicate operation which cannot be controlled even with a powerful

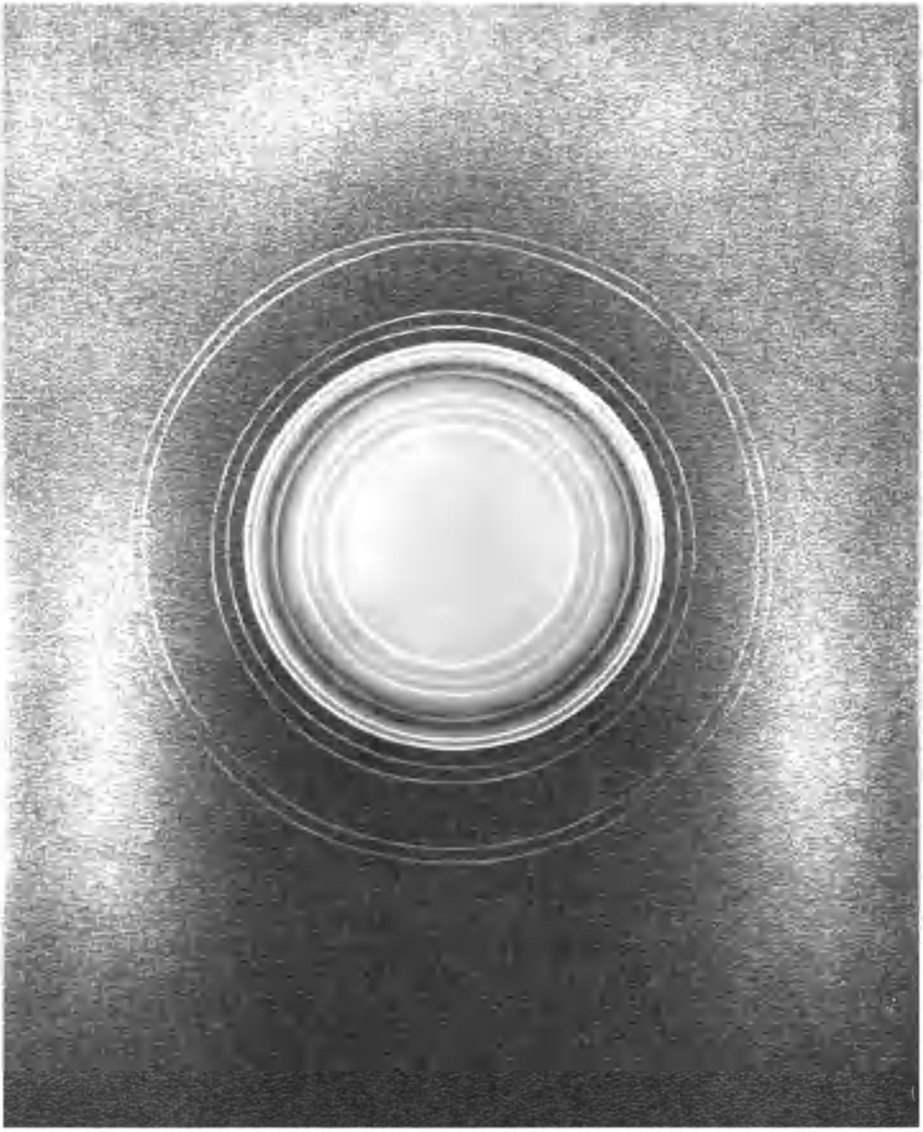
optical microscope. A section which is to be observed in a transmitted electron beam must be very thin. Its thickness, if this word may be used in this case, must be only 10 millimicrons, that is, it must be 38 times as small as the shortest wave-length of visible light. This value is at the limit of the resolving power of the electron microscope.

Superthin sections such as these are made with a special device called the ultramicrotome. With the aid of the ultramicrotome cuts can be made from 10 to 150 millimicrons thick, accurate within the limits indicated to 5 millimicrons. Such accuracy is not required even in the latest models of metal working machines. The knives of the ultramicrotome, made of special glass or of diamond can cut sections not only of soft tissues, but even of metals. The maximum surface area of the cut is 3×4 millimetres.

The images of several objects of electron microscopy are shown in the figures, as well as an electron diffraction

Beta-carotene crystals. Courtesy of the Laboratory of Electron Microscopy of the U.S.S.R. Academy of Sciences.





Electron diffraction pattern of a crystal. Compare this photograph with that of light diffraction, shown in Chapter I. Courtesy of the Laboratory of Electron Microscopy of the U.S.S.R. Academy of Sciences.

pattern. The first photograph is a negative image of a tomato leaf cell (one cell!) affected by the tobacco mosaic virus. The worm-like lines inside the cell are the virus particles. In the second photograph we see the images of bacteria with flagella and a few phage particles. The bacteria could be seen under an ordinary microscope, but then neither their flagella nor the phage particles could be detected. The third photograph is an image of the crystals of an organic substance called beta-carotene. As you see, these crystals themselves are very small. How is their structure to be studied? A study of the electron diffraction patterns produced by these crystals may be useful in this respect. But these are not easy to obtain, because a beam of electrons speeded up in the accelerating electrostatic field of the microscope readily breaks up the structure of crystals of organic compounds of biological origin. Only just recently scientists succeeded in obtaining the electron diffraction patterns of such objects. The electron diffraction pattern is especially interesting to us because of its similarity to the light diffraction patterns we discussed earlier in this book.

We have given images of objects studied in biology. But the electron microscope is employed just as extensively in other branches of science and engineering; it is used to advantage by physicists, chemists, metallurgists, and others.

PHOTOGRAPHY AND CINEMATOGRAPHY

To see once is better than to hear a hundred times.

Imprinted Light

Photography has served mankind faithfully for over a century. At present the number of amateur photographers the world over is immense. It takes a highly developed up-to-date photographic industry to satisfy their demand for cameras and other equipment, films, paper, chemicals and many other necessary things.

But this industry would hardly occupy the important place it does in the economics of highly developed countries, were photograph fans its only consumers. Despite the tremendous number of exposures made daily at all parallels and meridians, of beloved ones, relatives and friends, splendid landscapes, sporting events, picnics and voyages, despite the wide propagation of amateur cinematography, this does not constitute the greater part of the total photographic and cinematographic work done in the world at present.

It is very difficult to determine the exact figures for even the quantity of photographic materials used annually.

But to get at least a rough idea of their consumption, we can carry out a very simple calculation. Ten million possessors of photographic cameras exposing five rolls each per year use up over 80 thousand kilometres of film. A film strip that long can engirdle the globe twice at the equator. Making an average of 500 prints per year (including rejects) 13×18 centimetres in size, these 10 million amateurs will consume 120 square kilometres of photographic paper and an enormous amount of chemicals.

But this quantity is still much smaller than that consumed by professionals in art, documentary and scientific photography and cinematography. Suffice it to say that a one-and-a-half hour motion picture takes up about 3.5 kilometres of ordinary film. Over a thousand such films are put out annually all over the world, each of them being issued in several score, and not infrequently several hundred, copies. And the quantity of photographic materials consumed in science and engineering amounts to no less, we daresay, even more than this.

The human visual memory is capable of remembering a great deal. But man forgets still more. And even what seemed to have impressed itself in minutest detail in the memory, not infrequently proves to be right only generally, only in the main, on verification. However, even what man remembers quite accurately and has a clear idea of in his mind, he cannot express adequately in words. Besides, the visual memory is very subjective: two eye-witnesses of the same event are likely to tell about it differently, though both their stories contain nothing but the truth.

Man has long been aware of this property of his and strived to make up for it by means of drawings. It may be said that some artists reached absolute perfection in drawing technique. One magazine carried several photographs of old streets and squares made specially by investigators to match them with the paintings of certain old Dutch masters, showing the same streets and squares. The accuracy of perspective and detail in these paintings was not inferior to the photographs.

But think how much time and energy was required even on the part of the most talented master to attain such a striking likeness! And with the aid of a camera anybody

can do just as well, and even better in a fraction of a second.

It is difficult to tell about a photograph. It has to be shown. That is its direct designation. And therefore the story of photography in this book is not limited to the chapter about it. Whatever the book deals with, wherever possible, the text is made clearer by photography—the great toiler of science and engineering. Only photography makes it possible to talk so easily about complicated phenomena and things. Only it gives a graphic idea of these phenomena and things.

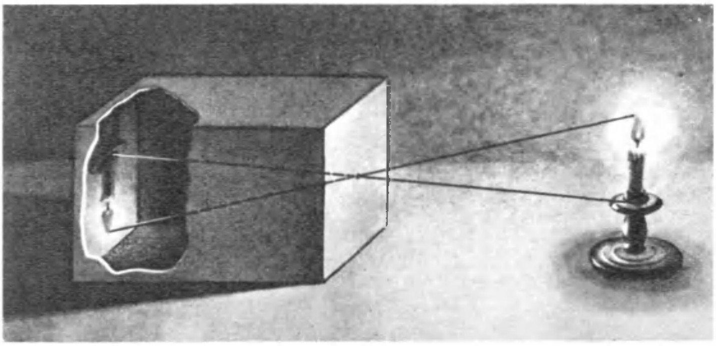
A Ray of Light in a Dark Room

No invention, be it of ever so little importance, is born of nothing, on a bare spot; it always has its predecessors. The latter are often widely known, but seen quite unrelated to one another. The connecting link between them is very difficult to discern, and can be found only when you know what you want to find, when the idea of the invention is formed already and wants only concrete means for its embodiment.

The distinguishing feature of the genuine inventor is that he knows how to find this connecting link. But another no less characteristic feature of the inventor is his ability to sense and understand the requirements of his time. People possessing these remarkable qualities are not so rare. That is why it has not infrequently occurred that important inventions were made independently and almost simultaneously by several people.

This can be illustrated very vividly by the example of the telephone. Graham Bell, its recognized inventor, filed his claim at the Washington Patent Office on March 14, 1876. And only two hours later Elisha Gray applied to the same Office for a patent on a telephone very similar to Bell's. It took Bell twelve years to prove his priority, which was contended not only by Gray, but by a dozen other claimants.

The number of inventors of photography was also not so small. But here the question of priority evoked no such



The tiny opening in the camera obscura acts like the lens of a present-day photographic camera, but it lets through hundreds of times less light.

heated arguments. Two Frenchmen are acknowledged as the "fathers" of photography: Joseph Nicéphore Niepce and Louis Jacques Mandé Daguerre, the latter being an artist by profession. Their "offspring" saw light, or rather, imprinted light, for the first time in 1837. It was recognized officially on January 7, 1839, when a report on photography was made at a sitting of the Academy of Science in Paris.

Many of us have probably heard the expression "camera obscura", but possibly not all of us know what it is. Literally, camera obscura means "dark room". That is actually what the first camera obscura was. In contrast to ordinary dark rooms, light entered them, but only through a very small aperture made in a tightly closed window shutter or in the wall, and not through any accidental slits or chinks. Such a small aperture* is similar to a lens in action. On passing through the aperture the light rays fell on the opposite wall which was whitewashed for the purpose, or on a white screen placed in their path, and produced an inverted image of the landscape or any objects that were put before the camera. Of course, the image could be seen distinctly only if the room was well darkened, and even then, only on bright sunny days. To make the image crisp the aperture had to be very small, and the amount of light

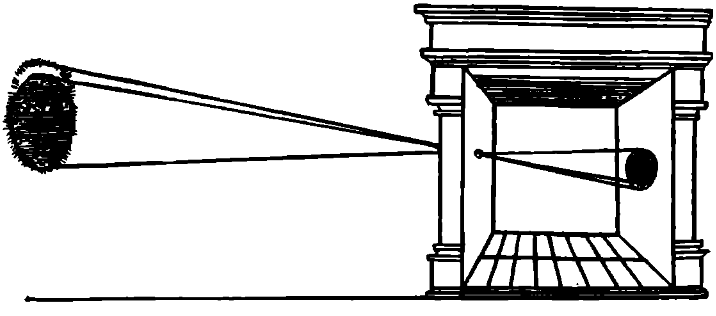
* But not so small as to cause diffraction.

that passed through it was much smaller than through the poorest lens.

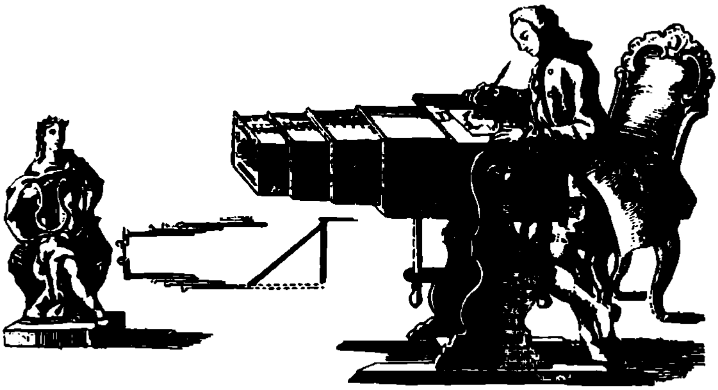
The camera obscura has been known for a very long time. Until not long ago its invention was credited to several European scientists: Roger Bacon, Leon Battista Alberti, Leonardo da Vinci, Giovanni Battista Porta. But it had been described long before them by the Arabian scientist abu-'Ali al-Hasan, also known as ibn-al-Haytham. We mentioned him in the beginning of this book. He lived from 965 to 1038 A.D. and wrote a treatise on optics (Opticae Thesauruss) which was well known in the Middle Ages. The European scientists of the Middle Ages latinized the author's name to Alhazen.

The camera obscura is described in ibn-al-Haytham's work. However, it was not even he who invented it. From his work it can be understood that the camera obscura was known to Arabian scientists, who knew a great deal for their times. They knew the structure of the human eye, also essentially a camera obscura, only a highly perfect one, the tiny aperture through which the light enters being substituted by the cornea and the crystalline lens, which allow considerably more light to pass through.

If we place a sheet of paper in the path of the light in the camera obscura we can produce very accurate drawings by tracing the outlines of the objects with a pen or



This drawing is from a very old manuscript. It depicts the camera obscura with which the solar eclipse of 1544 was observed.



This camera obscura was used by artisan drawers in the XVIII century.

pencil. Scientists took advantage of this and since olden times have used the camera obscura for sketching various natural phenomena. A book has come down to us written by the Hebrew philosopher and mathematician Levi ben Gershon (1288–1344) who lived in Province, in which he wrote that he observed an eclipse of the Sun by means of a camera obscura.

These cameras were widespread right up to the invention of photography. They were employed by naturalists and artisan portrait painters and by amateurs. In the long years of its existence the camera was greatly perfected, the small aperture being replaced by a lens, and the size of the camera being decreased; the image in these cameras was projected on to translucent or wax paper to make it visible from the outside.

In optical principle all types of modern cameras do not differ from their ancient predecessor. But the difference in the method of registering and retaining the image is immense. In the camera obscura this was done by the slow human hand, which, owing to the properties of vision, recorded the outline of the image fairly well, but caught the gradual transitions of light and shade much worse. In the photographic camera this is done automatically and almost in-

stantaneously—the light leaves its own traces on the photographic emulsion.

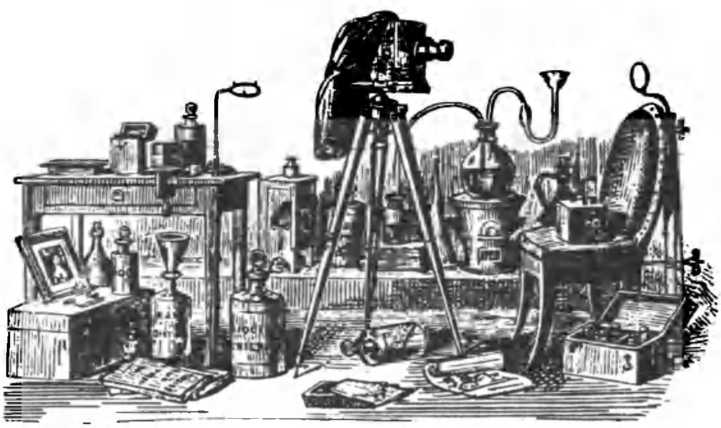
And this task, the task of making light record itself, was the first that had to be solved by the inventors of photography. Chemistry helped them to do this. Some facts about the action of light on certain compounds were already known to this science. Moreover, Niepce and Daguerre's predecessors had already obtained light images, but none of them knew how to fix them, how to protect the image, once obtained, from the further action of light.

The first to succeed were Niepce and Daguerre. And almost simultaneously with them a solution was found by the Englishman William Henry Fox Talbot.

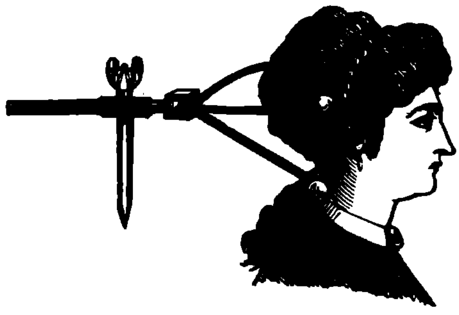
You can see here a reproduction of the first photograph made by Niepce. It is quite obviously far from perfect. Next we see a copy of the first daguerreotype made by Daguerre himself. Its quality is quite satisfactory, no worse

The first photograph in the world. It was made by N. Niepce from the window of his home.

The first daguerreotype, 1837.



Equipment for daguerreotypy.



To avoid blurring the face, the subject's head had to be kept in place by means of a special clamp.

than that of photographs made by many present-day beginners.

Daguerreotypy found wide application. But it had important shortcomings. First of all, daguerreotypes could not be multiplied by photographic printing. An impression on a daguerreotype plate was always the only one, because the plate was made of metal coated with a very thin layer of silver. Another major disadvantage of daguerreotypy was the very low sensitivity of these plates. The picture could be made only in very bright light, and even then, with a very long exposure time. To keep the subject being photographed (one might call him the patient) from moving, his head had to be held in special clamps. But notwithstanding, it was difficult to get a good picture this way. Often the eyes and mouth came out blurred, and the expression of the face was always tense and unnatural.

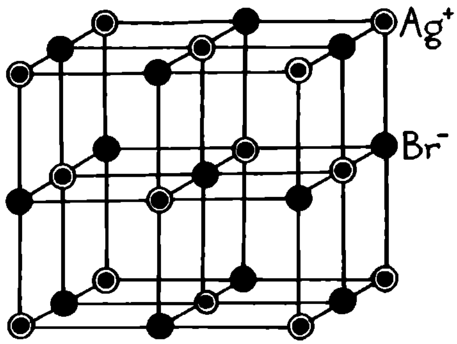
In the early fifties of last century daguerreotypy was already being forced out by photography on wet glass plates. They had to be prepared just before exposure. A plate coated preliminarily with a layer of collodion was dipped in a silver nitrate solution in the dark and then the picture had to be made immediately, before it dried. But the advantage of this method was that as many prints as desired could be made from it. The picture of the Moscow Kremlin cathedrals shown here was probably made on such a plate.

One of the photographs made on wet glass plates in Russia, in 1852.

Dry photographic plates with silver bromide emulsions made their appearance in the early seventies of last century. Since then, and to this day, glass plates are widely used in photography, though they have long been crowded by photographic films.

Photons, Silver and Chemistry

The sensitive layer of present-day films and plates is an emulsion, a suspension of microscopic crystals of light-sensitive silver bromide in gelatine. Special machines spread this emulsion in a thin layer on film, glass or paper, after which it is allowed to dry. The dry layer is very thin. In general purpose photographic materials it averages 16 microns. However, the silver bromide crystals are so small



This is a diagrammatic representation of the crystal lattice of silver bromide.

that the 16-micron coating accommodates from 20 to 40 layers of them. One square centimetre of this film holds from 50 to 500 million such crystals. But despite their great number, most of the crystals do not contact each other: they are as if enclosed in tiny gelatine capsules.

The crystal lattice of the chemical compound between silver and bromine is cubic in shape, with bromine and silver ions at the corners of the cube. Any silver bromide crystal is cubic in shape and is built up of separate minute cubes.

When a bromine atom combines with silver it takes one electron away from the outermost orbit of the silver atom. The bromine ions formed as a result of the reaction carry a negative charge each, and the silver ions, a positive one. The oppositely charged ions attract each other, and are held together in the crystal lattice by this force of attraction. In the inner parts of the lattice each silver ion is surrounded by six bromine ions and each bromine ion, by six silver ions.

Now, what happens when light rays fall on the emulsion? We shall be able to answer this question if we recall what we know about the nature of light and about one of the types of interaction between light and substance. Many of our readers have probably already guessed what is coming. Photons, of course. Only with their help is it possible

to explain why light leaves its traces on the emulsion, or, in other words, to build a theory of the photographic process.

On penetrating the crystal lattice photons, as in the case of photoeffect, yield their energy to the electrons. The first to receive it are the electrons taken away from the silver atoms. More accurately, these electrons require the least energy to be liberated, to be removed from the bromine ions. On yielding its electron the bromine ion turns into an electrically neutral bromine atom. At the same time the electron begins to roam about the space of the crystal lattice, being attracted by the positive silver ions and repelled by the negative bromine ions. It is finally drawn towards one of the silver ions where it occupies the empty orbit. Thus, the positively charged silver ion is reduced to an electrically neutral atom. The attractive force which had held the silver and bromine ions together, disappears, and one of the numerous bonds in the crystal skeleton is broken, thus lowering the strength of the latter.

If the light is intense and the time of its action on the emulsion is long enough, a sufficient amount of photons enter each of the crystals and under their influence the chemical bonds are all broken. The silver bromide decomposes into its constituent parts, bromine and opaque metallic silver. The emulsion grows black and also becomes opaque.

But if an image is projected on to the surface of the plate, the various parts of it are illuminated differently. The number of photons coming to each part will be different. And, therefore, the degree of darkening of each area will also be different: the more strongly illuminated areas will darken more than the less strongly illuminated ones. In this way we can obtain photographs without developing them. But very long exposure times are necessary for this. This is how prints were made not so long ago on so-called printing-out paper. A sheet of this paper was placed under the negative and put out into the bright sunlight. The prints were of a very pleasant sepia colour. After printing they could be fixed in the light. The accompanying photograph gives you an idea of how photographic prints were made in Fox Talbot's studio.

Talbot's studio, 1845. The studio

It is all very well to make prints this way, but it is no good for negatives. And the negative process has long since been carried out otherwise. Amateurs know that an exposed plate or sheet of paper cannot be distinguished from an unused one. Its surface is just as uniform and clean as before exposure. Not the slightest traces of the image can be seen on it. But the difference between an unused and exposed plate becomes perceptible soon after they have been immersed in a tray of developer. Dark spots begin to appear on the light surface of the exposed plate. Hardly noticeable at first, they gradually grow darker and darker, then more and more contrasty, and a few minutes later the formerly invisible image already appears on the emulsion. An unused plate remains just as light as it was for a long time, but after this it will grow uniformly darker.

could work only on clear sunny days.

The invisible image stored in the emulsion of the exposed plate is called a latent image. To get such an image only very small exposure times are needed. Thus, it is known that in sensitive emulsions to obtain one developable photographic grain which consists of a large number of tiny crystals grouped very close to one another, about 1,000 photons are required. When obtaining a latent image it is no longer necessary for the light to reduce a large number of silver ions to atoms. It is sufficient for the photons to cause just a few "breaches" in each of the exposed crystals. The rest is done by certain chemicals which react with the silver bromide crystals. These chemicals are contained in the developer.

When we immerse a plate, whose emulsion has already been subjected to photon bombardment, in a tray of devel-

oper the developing agent penetrates the thin gelatin partitions and enters into a complex chemical reaction with the silver bromide crystals. During this reaction the latter decompose, as they did under the action of light, into their constituent parts, bromine and silver. But the rate of this reaction is different in different parts of the emulsion. The more bonds broken in the crystal, and therefore, the weaker the chemical stability of the latter, the higher the rate of the reaction. The reaction of reduction of metallic silver occurs much more slowly in crystals whose bonds were not greatly disturbed. But if we were to leave the plate in the developer for a very long time the emulsion would become dark all over and the image would disappear.

However, we never do so. We allow the reaction to proceed only until the image comes out in all its details. Then we interrupt it by washing off the developing agent with water, and start the next stage of treatment, fixing. The fixing solution removes all the residual undecomposed silver bromide from the emulsion. After this the plate, film or paper will not be affected any more by light.

Knowing the causes of the photoeffect and the quantum properties of light, we can forecast such a property of photographic emulsions as the dependence of their sensitivity on the wave-length. We remember that the longer the wave-length, the smaller the energy of the photon. And the smaller the energy, the more difficult it is to liberate the electron captured by the bromine ion. Hence, at a certain wave-length the photons will not be able to knock out electrons at all. Thus, like photocells, photographic emulsions have a red boundary of light sensitivity. Owing to the existence of this boundary, orthochromatic plates and films, and photographic paper can be developed under a bright red and even orange light without incurring the risk of exposing them.

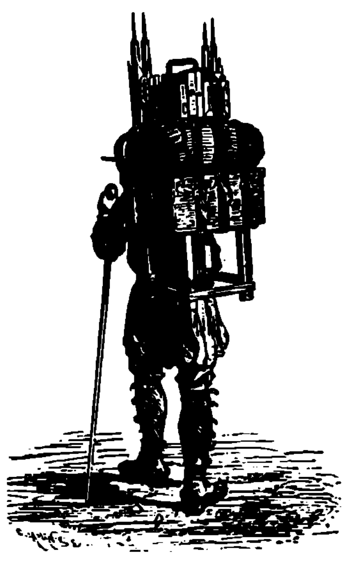
Amateur photographers know that there are other grades of photographic materials which can be treated only in complete darkness, because their red sensitivity boundary is shifted into the range of longer light waves. At present special grades of negative films are put out, sensitive to infrared rays, though not of very long wave-lengths.

But as to blue, violet and ultraviolet rays, not to mention

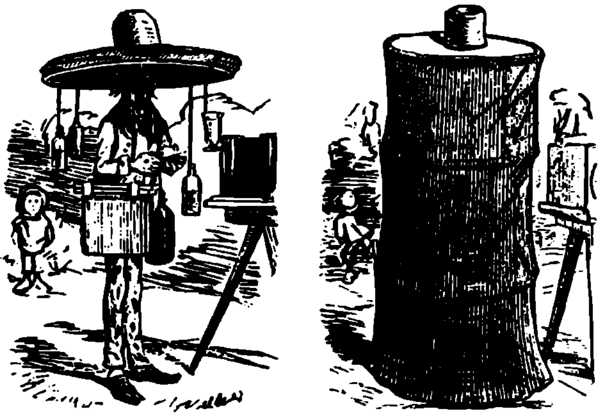
x- and gamma-rays, all plates are sensitive to them. True, short ultraviolet rays do not act on ordinary gelatin-base emulsions. This is due to the fact that gelatin is opaque to such rays. Photographs in the ultraviolet are made on emulsions not containing gelatin.

Rivals or Friends?

Photography spread very quickly in Europe. The photographer became one of the indispensable members of expeditions and voyages, historical events and modest family celebrations. The camera came to occupy an honoured place in the scientist's laboratory, became the hobby of a multitude of enthusiasts. The new invention gave birth to many new professions, and soon the figure of the travelling photographer and the sign of the photographic studio became common on the streets of large, and subsequently, of small towns.



There was a time when the tourist-photographer looked like this.



An old English caricature of a street photographer.

Photography was probably one of the few inventions which had no serious enemies in the initial period of its development. Even artists were not particularly worried about its appearance, though they had more grounds than anybody else to be troubled about it: there were those who from the very first foretold the complete triumph of photography over painting.

Art photography, indeed, appeared and made great progress in a very short time. Still, painting was none the worse for it. Doubtless, photography had a great effect on it. It made painters and graphic artists seek new means of expression which are unavailable to photography, a new approach to the interpretation of nature, and, which is especially important, to take a new view of the tasks of the fine arts—genuine art survived the competition with photography. Artists came to understand that it was foolish and wrong to try and compete with photography in fields where any mediocre photographer could do better than the most talented artist. And they found new trends, new fields which photography will never be able to dominate. Painting and graphic art came out of this competition renewed, still more expressive and beautiful.

Art photography did not kill art, but painting and especially graphic art had to yield a number of fields where they had hitherto reigned supreme. For example, the formerly widespread art of miniature portrait painting disappeared almost altogether; croquis artists, who had formerly furnished newspapers and magazines with drawings, "died out"; the illustration of scientific, popular science and technical books passed largely into the hands of photographers.

But if we stop to think of it, the fine arts yielded to photography only those fields in which they were essentially no longer arts, but trades; where the prime requirement was documentary authenticity, where it played the part of a chronicler and explainer or served to gratify clients by making their portraits "lifelike".

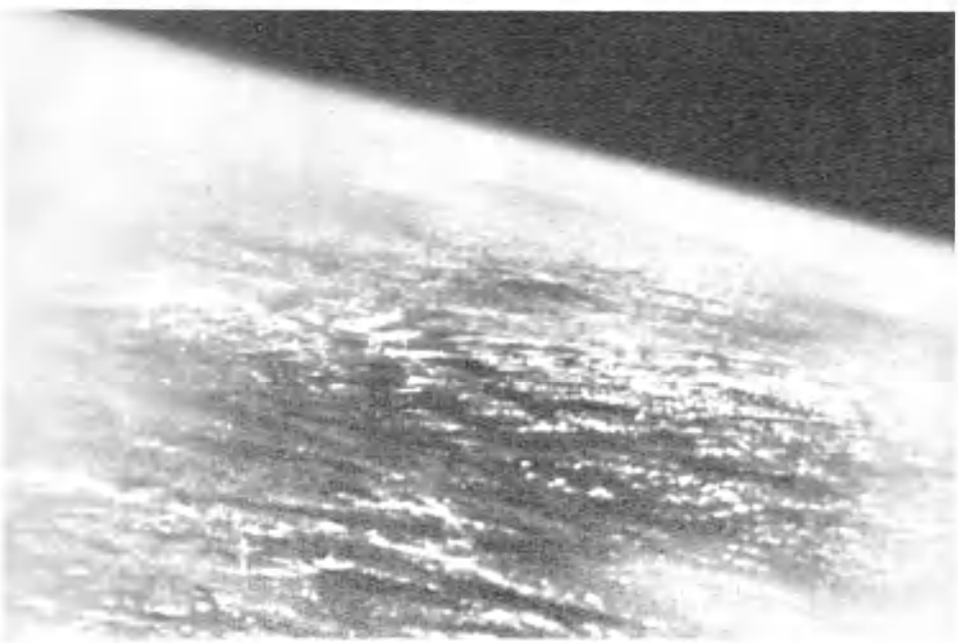
Using a camera is much easier than drawing. There are not so many good graphic artists in all the world, maybe a thousand or two. But anybody can be a photographer. The life of humanity, the life of our planet is rich in all kinds of very interesting events. However, few people are ever actually eye-witnesses of these events. All the rest have to content themselves with the not very accurate and at times contradictory stories of the witnesses. If there happens to be an artist among them he draws either from life or under the fresh impression. And then all who see his drawing get a much better and fuller idea of what the eye-witnesses tell.

But there are too few artists, and even if they did nothing but draw various events, they would not be able to cover even the most important of them. Besides, a sketch takes a considerable amount of time, and time is just what the participant or witness of the event is often short of. A drawing made from memory loses in accuracy, which in this case is the most important quality.

Nowadays, there are photographers (professionals and amateurs) in all corners of the earth, and present-day techniques make it easy for them to take large numbers of pictures very quickly. And any snapshot, even if it is not a very good one, is much superior in accuracy, detail and authenticity to the best documentary drawing.

These two qualities of photography—its mass nature and its genuine documentality—are of very great importance.

These photographs were published in the papers just a short time ago. But now they have already become historical. Thanks to them, we know what the hero-spacemen looked like in their space suits, what the Earth looks like when observed from space (see photographs on pp. 228-229).



This is also an historical picture. It has brought down to us the events of 1871 in Paris, when during the days of the Paris Commune the Colonne de Vendôme was pulled down.

Until not long ago such a picture would have been very difficult to obtain. The wings of many insects vibrate so rapidly that they can be photographed only at very high speed. What you see in the photograph is a cicada on the wing. No artist would ever be able to make such a drawing from life.

It is due to them that man's knowledge and ideas of the world around him have widened immeasurably.

Most of us never have a chance to travel. And though it is rather annoying, we do not get to see very many different villages, towns, and the more so, different countries. Notwithstanding, we know quite a bit about our planet. We can picture Moscow, Leningrad, London and Paris; we are acquainted with the wonders of Chinese and Indian architecture; we have seen more than once uninhabited deserts and the huge waves of the ocean tide. We know what various peoples look like, how they dress, how they live and work, how they rest, make merry and mourn. And we sometimes dream of what we have never seen in real life. We owe all this deep-rooted knowledge to photography.

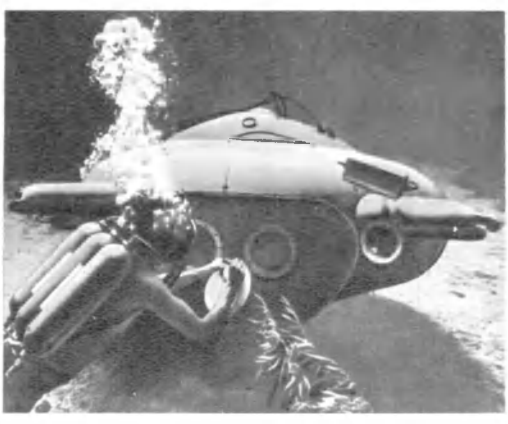
The All-Seeing Eye

Up till now we have been speaking about photographing what occurs in places accessible to man. But photography makes it possible to look into places which are inaccessible to "ordinary mortals": it can take pictures of the Earth from a rocket, record an atomic explosion or the actions of a test pilot under complicated flight conditions.

In recent years underwater photography has come into extensive use. If the depth is not great, the photographer goes down in a diving suit and with an aqualung. A light, mobile submarine boat called the "diving saucer" was built not long ago for investigating depths down to 300 metres. It accommodates two persons, the navigator and the observer. This boat carries up-to-date equipment. It has a gyrocompass, three-dimensional sonar, a radio telephone, a magnetic tape recorder and a large set of photographic and cinematographic equipment. The "diving saucer" has an arm—a hydraulic claw controlled from the cabin, by means of which soil specimens and various other objects can be collected from the bottom.

For the investigation of very great depths special submarine apparatuses called bathyscaphs have been built in recent years. They can easily descend to a depth of several thousand metres. And in 1960 the "Trieste" bathyscaph

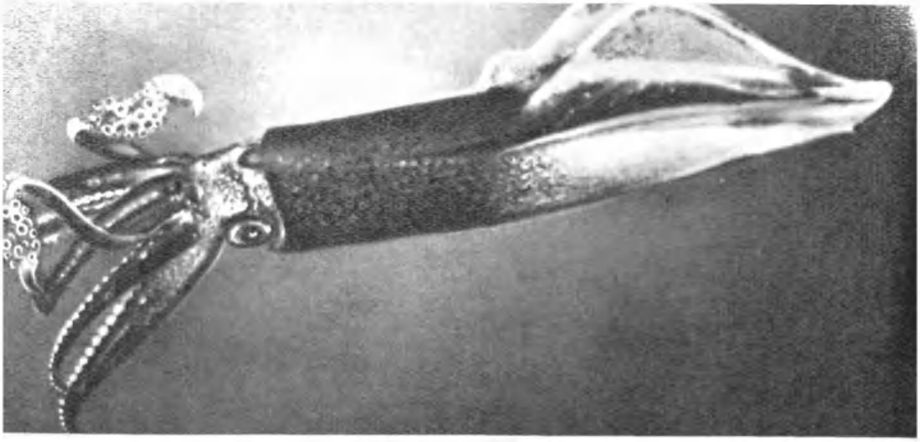
The "diving saucer".



The "Trieste" bathyscaph.

descended to a depth of 10.9 kilometres, into Challenger Deep near Guam in the Pacific.

The "Trieste" bathyscaph is a huge steel float with a spherical steel chamber having illuminators of thick plexiglas fixed to its bottom. The float is filled with a light liquid (most frequently gasoline) to keep it from being crushed by the tremendous pressure in the ocean depths. The steel sphere accommodates two observers and various apparatus. The bathyscaph is equipped with several powerful spotlights, making it possible to carry on observations and take photographs at great depths which are enveloped in eternal darkness. The bathyscaph is sunk by means of steel weights held by electromagnets. When the time comes to return to the surface the magnets are shut off, and the steel ballast remains at the bottom while the enlightened apparatus floats to the surface. Each descent of the bathyscaph is a very dangerous and complicated undertaking. The risk involved is very great. If only one of the weights fails to separate from the body the crew will remain at the bottom forever: there are as yet no means of life saving



The calmar, a sea mollusc. Giant calmars may be up to 18 metres long. Note its eyes.

at such depths in existence. And it must be admitted that the first bathyscaph crews must have been men of very great courage.

So far only a few pairs of eyes have seen the ocean floor at great depths. And if it were not for photography only the owners of those eyes could have a real idea of what life there is like. One of the photographs made by the crew of the "Trieste" bathyscaph at a depth of 7,000 metres is shown here. On it you see a deep-water fish. It has very long and thin fins. Scientists had known this fish very well before it was photographed from the bathyscaph, as such fish had been caught more than once by deep-water trawls. However, they had been unable to establish the designation of such long fins. They had assumed that the fish used them as feelers. But they were wrong. Observations and photographs of this fish made in natural conditions revealed their true designation: the fish uses these fins to walk, or rather hop along the ocean floor like a grasshopper.

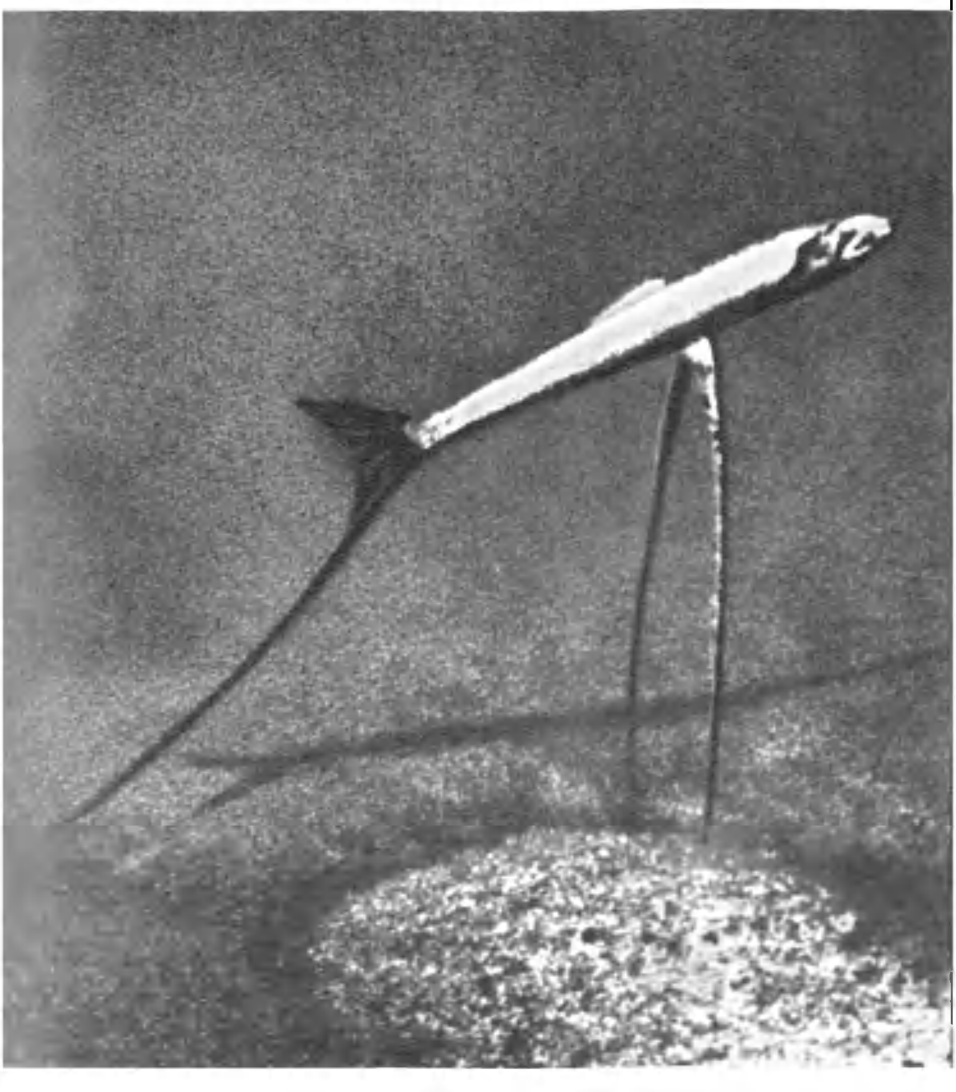
This fish was seen by at least two pairs of human eyes. But photography can see things which are inaccessible as a matter of principle to human vision.

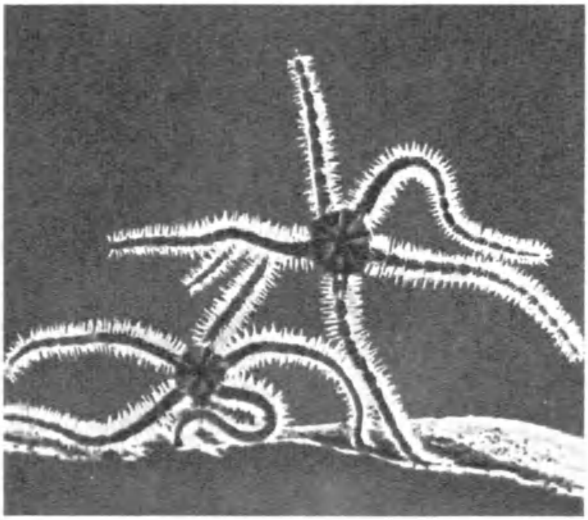
On p. 237 you see two photographs of a starry sky. They are very different. In one of them there are comparatively few stars, while the other shows an enormous number of

them. Still these are photographs of the same part of the sky, made at the same moment through a twinned telescope. What is the difference? It is, that one of the photographs was taken in blue rays, visible to the eye, while the other was taken in infrared rays.

Infrared rays have a very remarkable property. It is due to the comparatively large wave-lengths of these rays.

A deep-water fish which walks along the ocean floor on its fins.

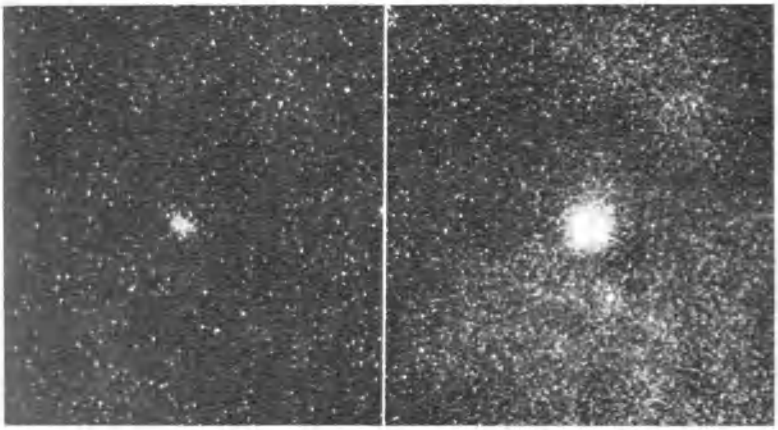




This is how starfish move.

Owing to this, they are scattered less by the clouds of interstellar dust and gas, and pass through them much more readily. The short-wave rays are scattered considerably by these interstellar clusters and are greatly weakened. And the stars can therefore not be detected by the eye even through the strongest telescope. They were detected with the aid of a photographic plate—not an ordinary one, but one that was sensitive to infrared rays. If scientists had not invented such plates, we should know much less about many of the more remote parts of the Universe.

But infrared photography is useful not only in astronomy. It is no less necessary for many terrestrial purposes. Very often distant objects are hidden from our view by a light mist. The effect of this mist can be eliminated by photographing in infrared rays. Distant objects become more clearly visible in such photographs than on the clearest day. True, all the surroundings look very strange: the sky is absolutely black, only very dense clouds can be seen on it; the foliage of the trees, which reflects infrared rays



Two photographs of the same part of the sky. The difference between them is that the left-hand one was made on an ordinary plate, while the right-hand one was made on a plate sensitive to infrared rays.

well, is white, as is the grass. However, for scientific purposes such a distorted colour rendition is not only no obstacle, but often even a great help, making it possible to see what is invisible by ordinary light. By the reflection of infrared rays by plants, healthy ones can easily be distinguished from diseased ones. The dissimilar reflection of infrared rays by different species of trees makes it easy to find out the distribution of vegetation in forest bodies from infrared aerial photographs.

The left-hand picture was made on an ordinary film, and the right-hand one on a film sensitive to infrared rays. Note the difference in the rendering of the sky, the foliage and the background.

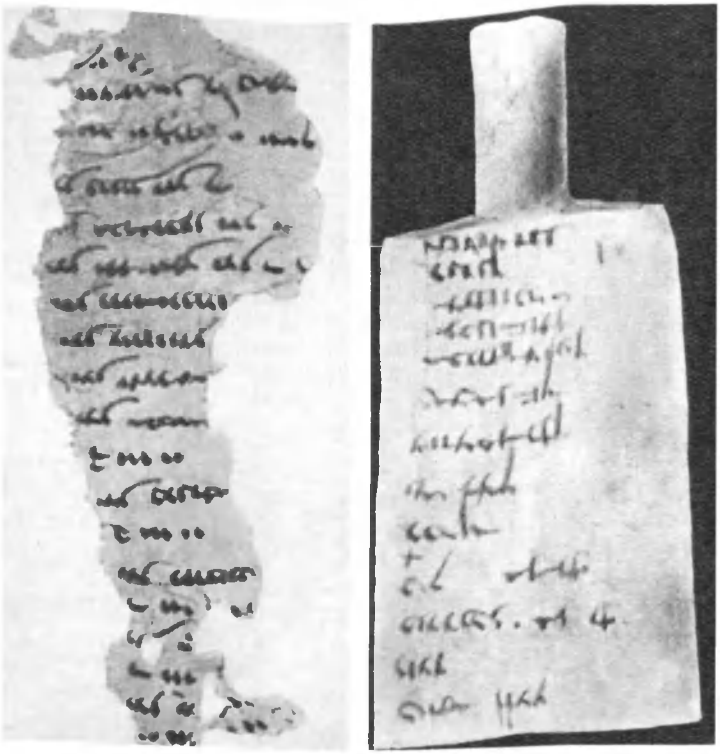
Very interesting photographs can be made at night in infrared rays. They are often made under the illumination of the invisible ray of an infrared projector, and then they differ little from day photographs. But if the pictures are taken without additional illumination, only those objects or parts of objects can be seen whose temperature is high enough. For example, plant chimneys, the heated parts of automobiles, aeroplanes or ships would be seen.

The maximal wave-length to which present-day infrared plates are sensitive is not very long—about 1 micron. But engineering is greatly interested in obtaining images in the longer-wave region of the spectrum. At present, methods have already been worked out for obtaining images in infrared rays with very long wave-lengths. But for the time being it may be said that at a wave-length of 7 or 8 microns we can get the heat portrait of a man, because in this range of wave-lengths man is a luminous body, that is, radiates his own light. With the aid of such photographs even malign tumors can be detected, because the temperature of the skin above them is a fraction of a degree higher than on the rest of the body's surface.

Ultraviolet and infrared photography is a great aid to investigators of old pictures, manuscripts and documents, and even help to expose criminals of various kinds. Texts erased by time or careless usage—extinct texts, as they are called—come back to life under these invisible rays, and being photographed, reveal their secrets to the investigator. This method of investigation also brings out into the open all kinds of forgery and falsification in documents.

We have almost all had occasion to visit an x-ray examination room and while awaiting our turn have peeped over at the greenly luminescent screen on which the outlines of the skeleton and vague blurred shadows of the internal organs of the person being examined could be seen. If a wooden dark slide with a photographic film is put in place of the screen such an image can be obtained without a camera and even without opening the slide. This is how x-ray photographs of various objects transparent to x- or gamma-rays are actually made.

In recent years wide use has been made of labelled atoms for investigating various animals and plants. La-



Infrared and ultraviolet rays helped to reconstruct the ancient text. This text was invisible in ordinary light rays.

belled atoms are radioactive isotopes of chemical elements. In chemical properties they do not differ from ordinary atoms and are capable of the same reactions. But the difference is that the radioactive isotopes are subject to radioactive decay, during which the atom emits gamma-rays.

Using labelled atoms scientists have been able to trace the innermost processes of metabolism, which are inaccessible to other methods of investigation, to study the distribution and determine the role of various chemical compounds in the organism and in plants. For example, it is

This is what is known as an autoradiograph, that is a photograph obtained by means of radioactive radiations. To produce this picture radioactive penicillin was injected into the mouse's bloodstream.

very important to medical workers to know the action of medicines on the various organs of an animal. For this purpose they have to determine first of all how and by which ducts the medicine is delivered to the internal organs, where it accumulates and where it is in short supply. This problem is solved with the aid of labelled atoms and photography. In this case, too, no camera is needed.

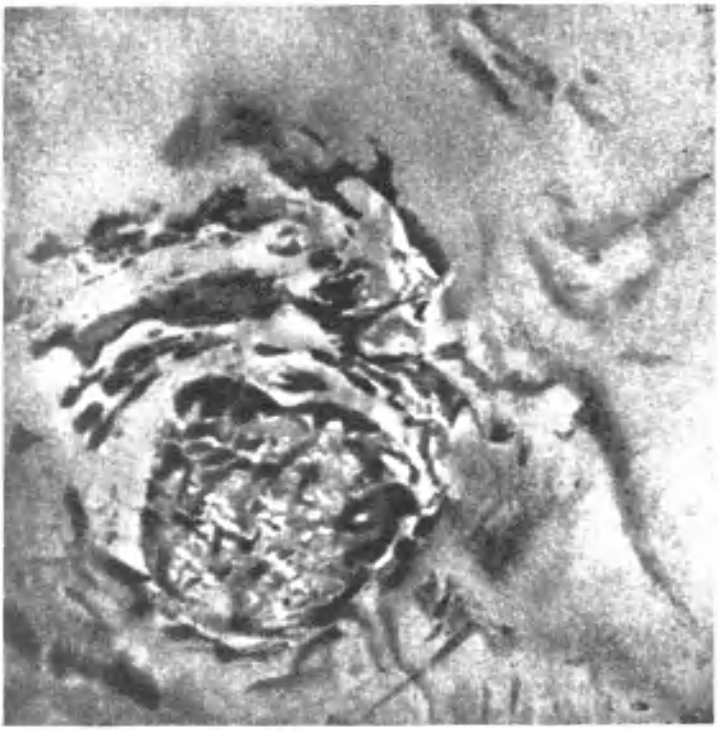
A photograph of this kind is shown here. In it we can see the places where penicillin accumulates in the internal organs of a mouse. To obtain this picture specially prepared penicillin, differing from that sold at any chemist's in that it contains labelled atoms, was introduced into the mouse's blood. The emitted gamma-radiations freely penetrated the animal's tissues and left their trace on a photographic plate.

Photography is a great help in compiling geographical maps for various purposes. Without aerial photography modern cartography would be quite unimaginable. It was aerial photography that made it possible to compile such detailed and accurate maps. It has enabled compilers quickly to take into account the big and small changes caused in the countenance of the planet by human activity and natural processes. It is used not only to photograph dry land, but also to compile quickly and accurately maps of the shallow areas of seas and oceans.

It is employed extensively by modern geology. Photographic aeroprospecting is one of the quickest methods of prospecting for new mineral deposits and determining the boundaries of their occurrence. Archaeologists also owe very much to photographic aeroprospecting. With its all-seeing eye it distinguishes the slightest differences in the colouration of plants in fields and makes it possible by these differences to determine the spots where the ruins of ancient structures and towns are concealed under a layer of soil or sand.

This gigantic swamped and forest-covered meteoritic crater was discovered just recently by means of aerial photography.

An aerial photograph of a desert beneath which the ruins of an ancient city were buried. Photographed in the morning.



Undersea exploration can also be carried on from the air, and in this way things can be seen that cannot be detected by other means. You see an aerial photograph of a submarine mud volcano.

The Three-Colour Theory in Action

In the chapter on vision casual mention was made of colour photography and it was stated that at present colour photographs are made everywhere by means of subtractive colour mixture. In this method any chromatic colour is obtained by subtracting its minus chromatic colour from achromatic white. But we did not say anything about how this is done in practice.

To understand the crux of the present-day method it is necessary at least mentally to go through all the stages of obtaining a colour photograph.

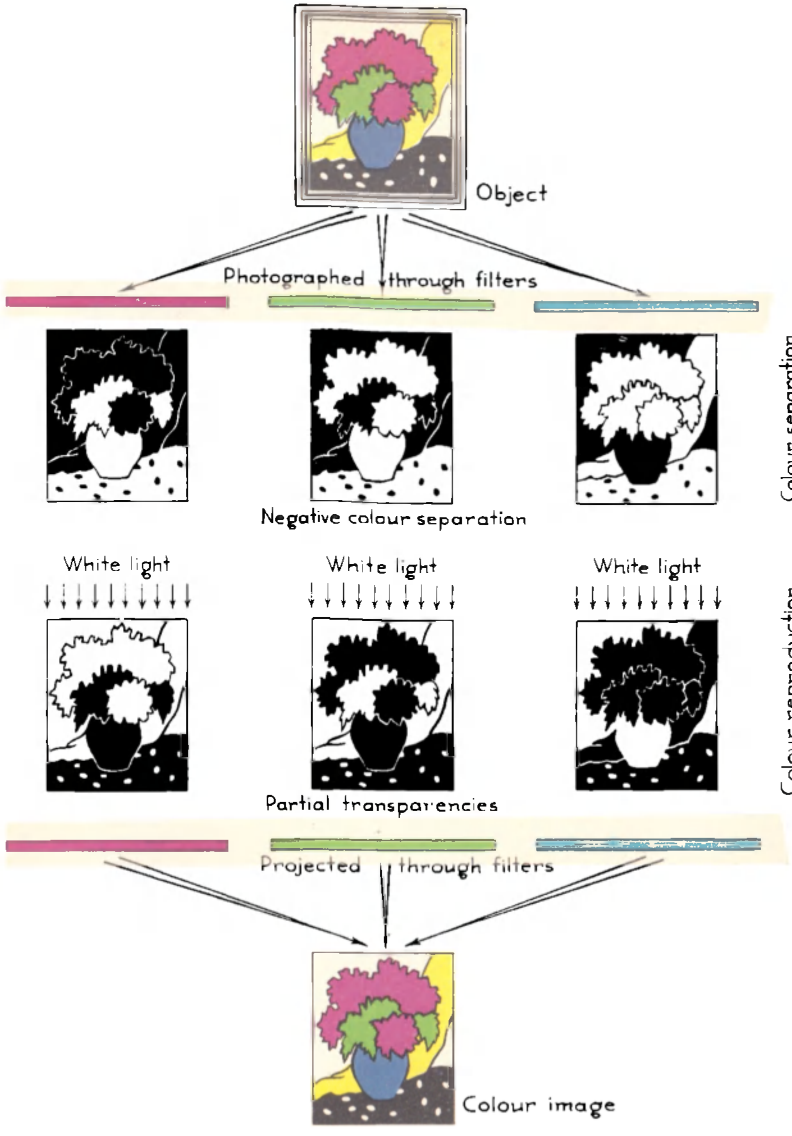
Suppose the subject is a bouquet of red dahlias in a blue vase. We photograph it three times, taking the first picture with a red filter, the second with a green, and the third with a blue one. As a result, we get three colour separation negatives which we shall call conventionally "red", "green" and "blue", though they are all only black-and-white. Then, as before, we print glass or film transparencies from them.

You know already what the difference between them is. On the "red" transparency the most transparent areas will be those with the image of the flowers, while the images of the leaves and especially the vase will be of low transparency. On the "green" transparency the image of the leaves will be transparent, while the flowers and vase will be dark. On the "blue" transparency the image of the vase will be transparent, and that of the leaves and flowers, dark.

If we insert such colour separation transparencies in a triple projector and project them on a screen through the three corresponding filters, taking care to superimpose them exactly, we shall get a very good colour image (better than Land's). But this is the additive method of colour mixture, not subtractive, because the rays of the three primary colours are added in this case.

A colour image can be obtained by the subtractive mixture method only after additional treatment of the transparencies. This treatment consists in dyeing them to the corresponding minus colours. The "red" slide would become blue-green after such treatment, the "green" one would become purple and the "blue" one yellow. It is important to remember that the areas which were the least transparent will be coloured the most intensively, whereas the light areas will remain uncoloured, that is, white. During such treatment the opaque metallic silver is replaced by the dye. The more reduced silver there was on any given area of the emulsion, the stronger it is dyed.

After dyeing, the image of the background, the table and the vase in the "red" transparency will be coloured blue-green, while the lemon and the red fabric will remain



Production of a colour image by the additive colour mixture method. Three colour separation negatives are made and from them three positives are obtained. Then the three positives are projected through the corresponding filters on to a screen. The result will be a colour image.

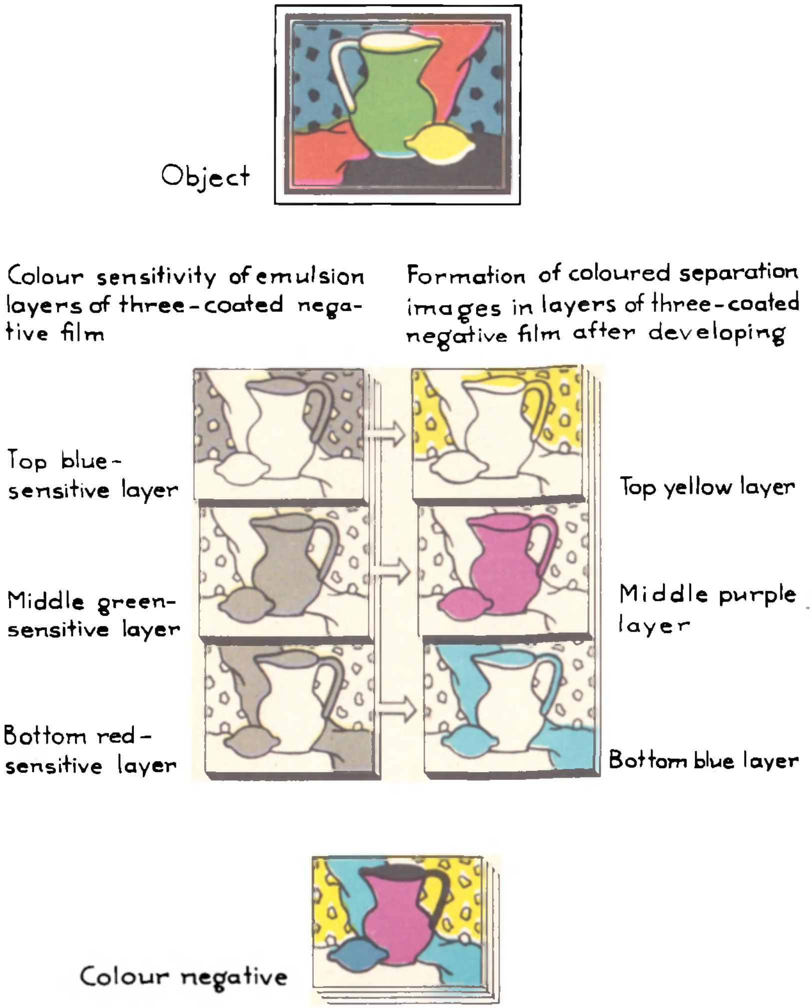


Diagram of colour negative process

Production of colour negatives and positives on three-coated materials
are the minus-colours with respect to

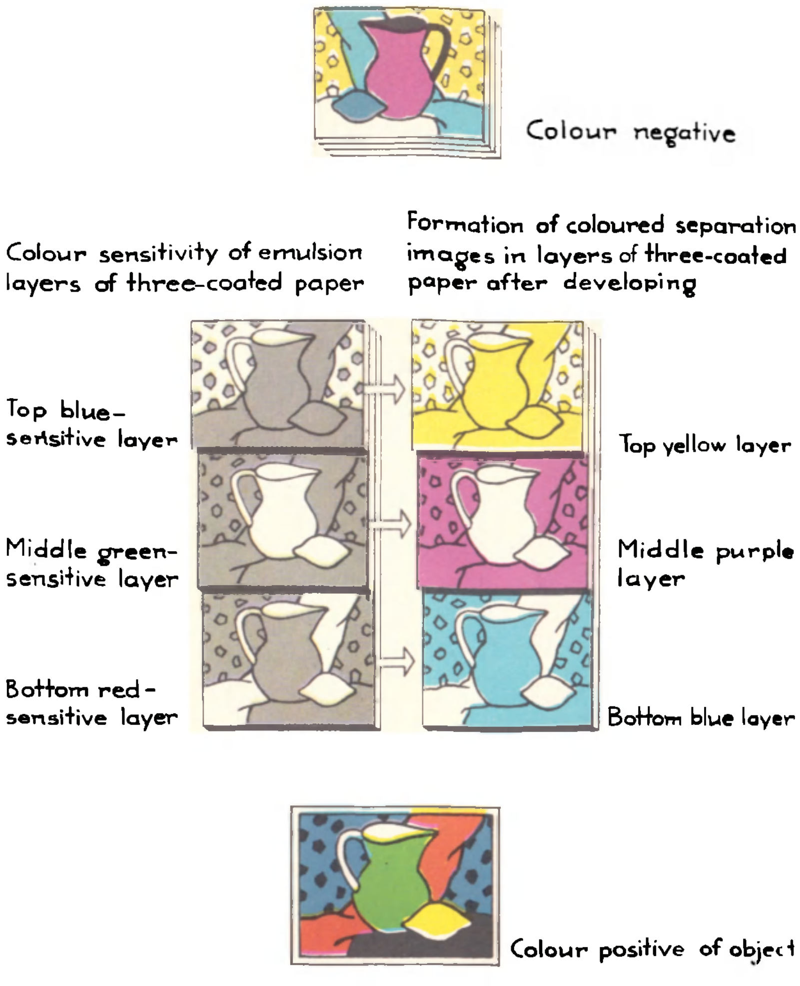
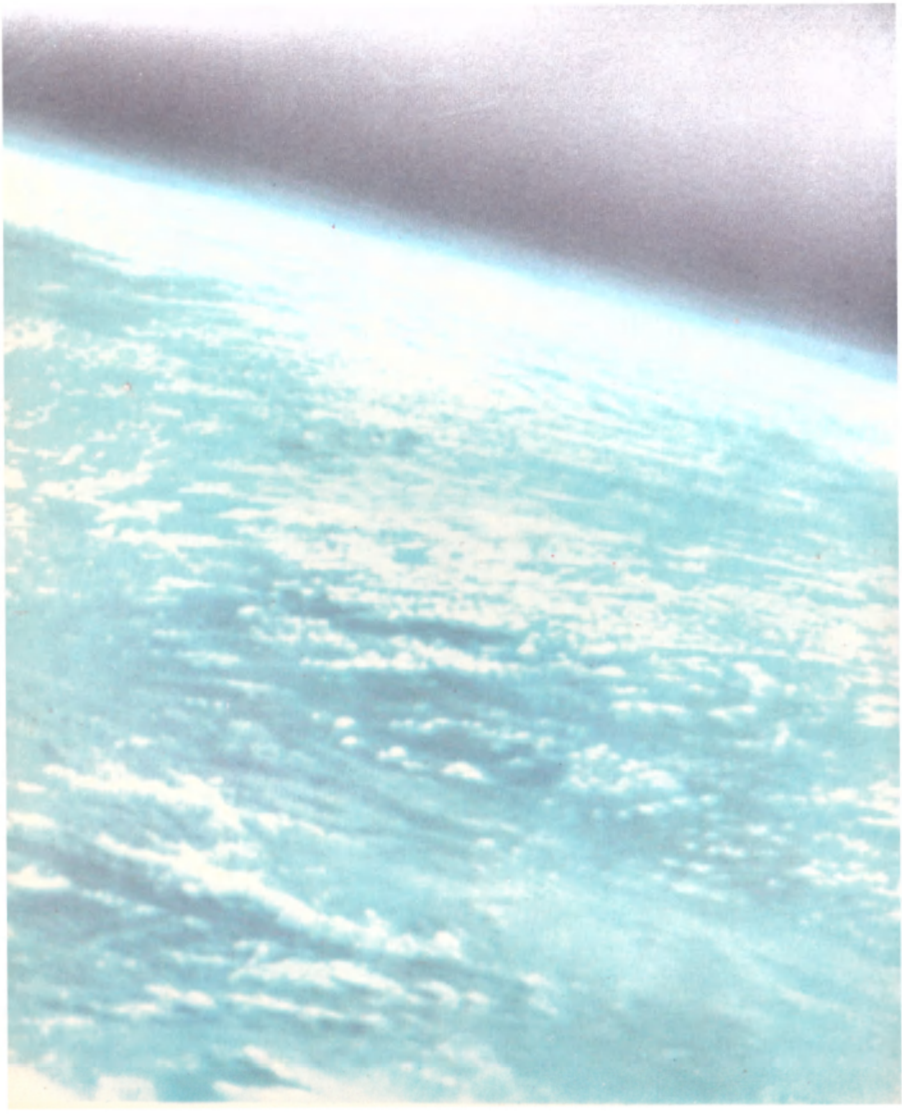


Diagram of colour positive process

by the subtractive colour mixture method. Left—negative; its colours those of the subject. Right—positive.



This picture of the Earth was made during G. Titov's historic flight.

white. In the "green" transparency the image of the background, the fabric and the table will be bright purple. In the "blue" transparency the vase, the lemon, the fabric and the table will be bright yellow.

If we now superimpose all three transparencies exactly on one another and regard them with white light passing through them, we shall see the colour image. When put together this way the slides can be projected on a screen with the aid of conventional apparatus. Wherever the white light passes through areas coloured yellow and purple we shall see red; where it passes through yellow and blue-green, we see green, and on passing through blue-green and purple, white light gives blue.

This is the basis of present-day colour photography. But its practical embodiment enables the photographer to get the results he wants in a simpler way. Instead of ordinary films or plates, the photographs are made with special three-coated films and paper, each layer of which plays the part of a single colour—separated negative or positive.

No filters are necessary for photographing, because each of the three light-sensitive layers possesses the necessary spectral characteristics. The top layer is sensitive to the blue rays of the spectrum. Beneath it is a layer sensitive to yellow-green rays; and the bottom layer is red-sensitive. Special organic dyes are added to each layer. When developed (ordinary developers are of no use for this) these dyes acquire colours, dyeing the top layer yellow, the middle layer purple and the bottom one blue-green. The resulting negative bears the minus colours of the subject and the positive. The negative is printed in the same way as black-and-white ones, but using special three-coated colour paper. True, to obtain the best colour rendition it is often necessary to employ special correcting light filters.

Colour photography is used not only to obtain art photographs. It is widely used in science and engineering as well, because data on the colour of objects often gives additional information that is very important to researchers.

We have already talked about aerial photography. The appearance of colour photographic materials enriched this field too. Have a look at the two aerial colour photographs reproduced here. They were made for the purpose of geo-

logical survey and mapping. Compare them with black-and-white aerial photographs and you will see how much more information concerning the terrain can be obtained from them. They enable an experienced interpreter to learn much more about the mineral deposits concerned by the colour of rock outcrops and even by the colour of the vegetation, than from black-and-white aerial photographs.

A very interesting field of colour photography is what is known as spectral zone photography. It differs from conventional colour photography in that the pictures are made in two or three narrow intervals of the spectrum, instead of the usual three primary colours. The choice of these spectral intervals depends on the purpose for which spectral zone photography is being used. If it is prospecting for a definite mineral, one or two of these intervals are selected from among the wave-lengths best reflected by that mineral, and the third interval is chosen from among the most characteristic wave-lengths in the reflected spectrum of the surface; most often, the latter is green, the colour of the vegetative cover. Prints from spectral zone negatives are made on colour photographic paper, but the colours that result are unnatural. However, they are such that it is easy to find the conventional colour characteristic of the mineral sought.

Autographs of Invisible Particles

If we were to continue our study of the nature of light, our next step would be to look into radioactive phenomena, cosmic rays, atomic structure, nuclear structure and nuclear particles. But though this is a very interesting and important field of physics, it has little to do with the subject of this book. You can read all about nuclear physics in the multitude of popular science books and articles published on that subject in recent years. Here, however, in our chapter on photography, it is worthwhile telling how it helps physics to penetrate into the deepest secrets of nature, bringing new wonderful particles into the field of view of the attentive researcher.

So far, no such microscopes have been invented which would make it possible to see molecules, to say nothing

of atoms and elementary particles. And, nevertheless, scientists have been able to detect many of these particles and to measure their mass, electric charge, determine their energy and speed.

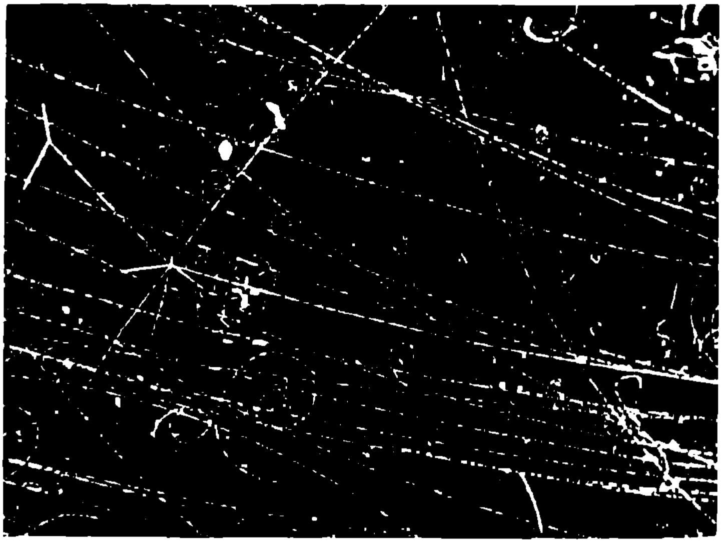
Photography has been a great help in this respect. Of course, it could not see the particles themselves either, but it has recorded their tracks very accurately. And this was sufficient to enable physicists to find out a great deal about the particles.

You have probably observed on occasion the sudden appearance in a clear sky of a narrow white band that grows continuously longer and longer—the track of an aeroplane flying at a great height. This is called a contrail. It appears when the exhaust gases come out of the engine into the cold surrounding atmosphere. The aeroplane may be so high up that we cannot see it with the naked eye, but by the contrail we can easily determine the direction of flight, the manoeuvres of the plane and at least its approximate speed. The aeroplane leaves its signature, as it were, in the sky, and it remains there for a long time, growing slowly dimmer and hazier.

A similar thing happens in a special apparatus known as the Wilson (or cloud) chamber. The inside of the chamber is filled with steam (steam is transparent; it must not be confused with fog). The pressure and temperature of the steam are maintained at such values that without foreign influence it will not condense. But if only a tiny speck of dust or an electrically charged particle gets into the chamber, the steam immediately begins to condense around them and minute droplets appear, forming a fog or cloud.

If one of the elementary particles possessing a sufficiently high velocity is let into the chamber through a special window, the particle will ionize the formerly neutral steam atoms it encounters in its path. The ions, which are electrically charged, cause condensation of the steam around themselves, and thus, the particle leaves its "autograph" in the chamber.

In other types of chambers designed for the same purpose, a superheated low-boiling liquid is used instead of steam. When particles travel through such a liquid they leave minute bubbles in their wake.



A photograph of the tracks of elementary particles in a bubble chamber.

It is impossible to study the tracks directly in the chamber; this would take too much time and would be not only inconvenient, but very inaccurate as well, the more so that the tracks left by the particles are short-lived. Therefore, scientists record the paths of the particles by means of an automatic camera operated by the particles themselves.

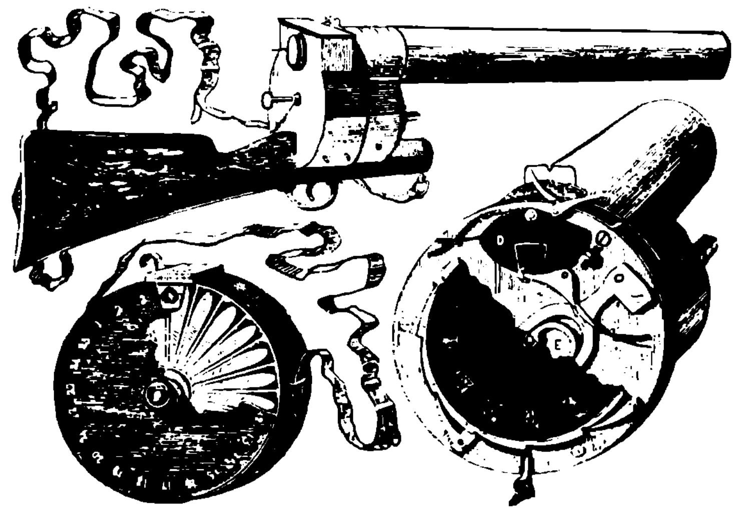
From the nature of the tracks left, their length, and the change in the direction of flight of the particles caused by the field of a powerful permanent magnet placed adjacent to the chamber, scientists can estimate the properties of the particles.

This is the method by which some of the particles known at present were detected. But in order to discover each one of them, an immense number of experiments had to be performed and thousands of photographs made. And only on a very few of them could anything new be detected.

The photograph reproduced here is one of the exceedingly lucky ones: among others, the tracks of antiparticles were detected on it.

In the 80's of last century Murray, physician and naturalist, and a great photography fan, designed and made a photographic camera of unusual appearance and possibilities. It looked very much like a gun. It had a stock, sights and trigger mechanism. But instead of a barrel this gun had a telescope lens, while the cartridges and clip were substituted by a drum with small photographic plates inserted in it. When the trigger was pressed the drum would revolve, the shutter would operate and take a picture. The faster the trigger was operated, the faster the pictures were made. A trained photographer could make as many as 10 or 12 exposures per second with a Murray gun, this being quite an unheard-of result for those times.

Like all real hunters Murray roamed through forests, fields and swamps looking for game. But the noiseless shots of his gun did not kill, nor do any harm; they did only good. When Murray's first photographs appeared naturalists and artists were astonished at how badly and in-



Murray's photographic gun.

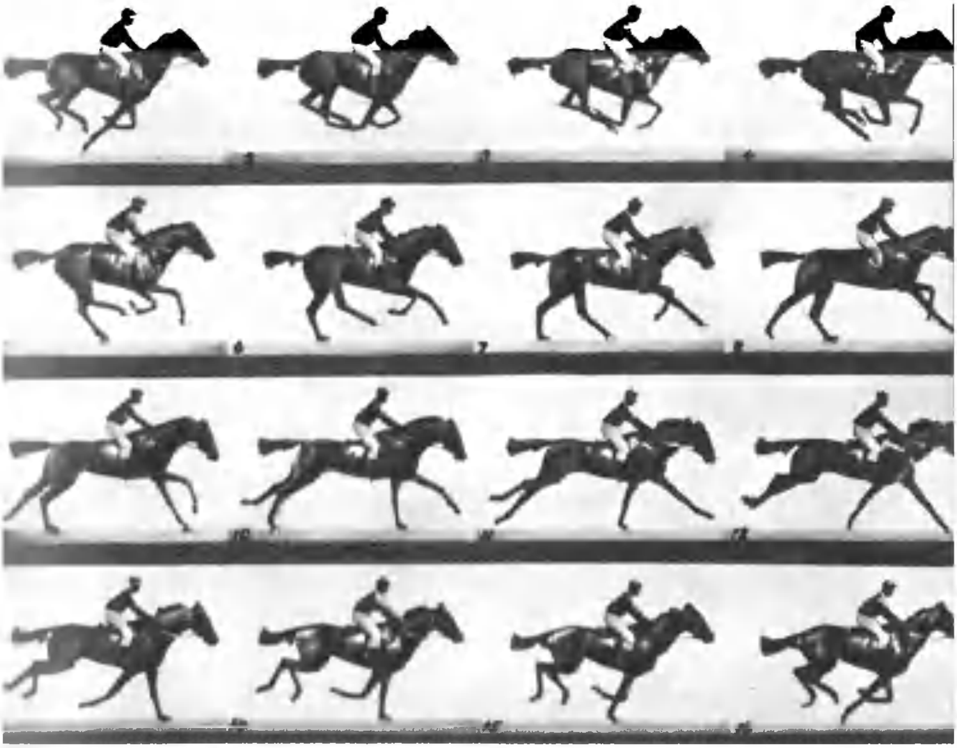
correctly they had imagined the movements of birds and animals. They saw that the separate phases of the movements of animals, obtained on the photographs were entirely different from what they had shown hitherto in their scientific drawings and pictures. This was all the fault of the human eye which is unable to resolve rapid movements into their separate phases or stages.

Photographs taken with the Murray gun were mostly viewed singly, the contents of each being studied separately. But sometimes, usually for fun, somebody would paste them on the disk of a cinematoscope, and rotating the disk like a top, would get the effect of movement. This had nothing in common with cinema. Yet, Murray's gun was no longer an ordinary photographic camera. It was rather one of the first predecessors of the cine camera.

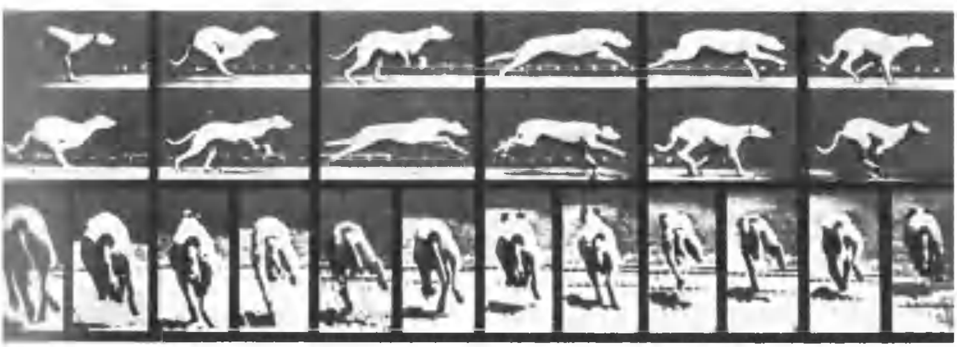
The first to cope successfully with the numerous technical difficulties and to make a special device for photographing and reproducing moving images was the great American inventor Thomas Alva Edison (1847–1931). True, not everything went smoothly with him at first either. The main cause of his failures was the weakness of the film on which he made his photographs—it tore too often. Only two years after he had started work, in 1889, did George Eastman, the founder of the Kodak Company, begin to manufacture nitrocellulose-base film. This film was of very high quality for that time. On learning this Edison bought from Eastman the longest piece of film the latter could make for him. Its length was 15 metres.

But this length of film was enough for Edison to make his first motion picture. It lasted only 13 seconds at a speed of 48 frames per second. One of Edison's early films showed two cats boxing, and another, a strong man doing exercises.

It is difficult to say why Edison picked on a camera speed of 48 frames per second. This was most probably due to the fact that the inertia properties of the eye were not known well enough at the time. Edison could have made his films last twice as long without lowering their quality by reducing his camera speed to 24 frames per second. At present, when the properties of the eye are known much better, the speed for ordinary cinema films



Movements of a galloping horse and a running dog. Cine-photograph.



is precisely 24 frames per second. At the turn of the century it was even lower—16 frames per second (the speed now used in amateur cinematography), which accounts for the fussiness and jerky movements of the characters in old films when such films are shown with present-day equipment.

Edison's kinetoscope was a very complicated, heavy and cumbersome apparatus. And for all that, it was so designed that the film could be viewed by only one person at a time. This design was Edison's great blunder, and the more annoying that he and his co-workers had performed successful experiments in showing films on a large screen. Moreover, one of Edison's assistants had even made a sound film, using the phonograph for this purpose.

But the great inventor held on stubbornly to his delusion. He believed that on the large screen cinema would not be a commercial success, that the public would soon lose interest in the technical novelty. Thus, commercial considerations came into contradiction with an excellent idea and buried it.

But it did not remain forgotten for long. In 1895, only a year after Edison started "commercial exploitation" of his kinetoscope, a film made by the Lumière brothers (Louis and August), owners of a photographic merchandise factory, was demonstrated for the first time in Paris. They took the path rejected by the American, believing that the idea of the large screen was the right one. And they proved that they were right. It is they, and not Edison, whom the world now recognizes as the founders of modern cinematography.

Stopping the Instant

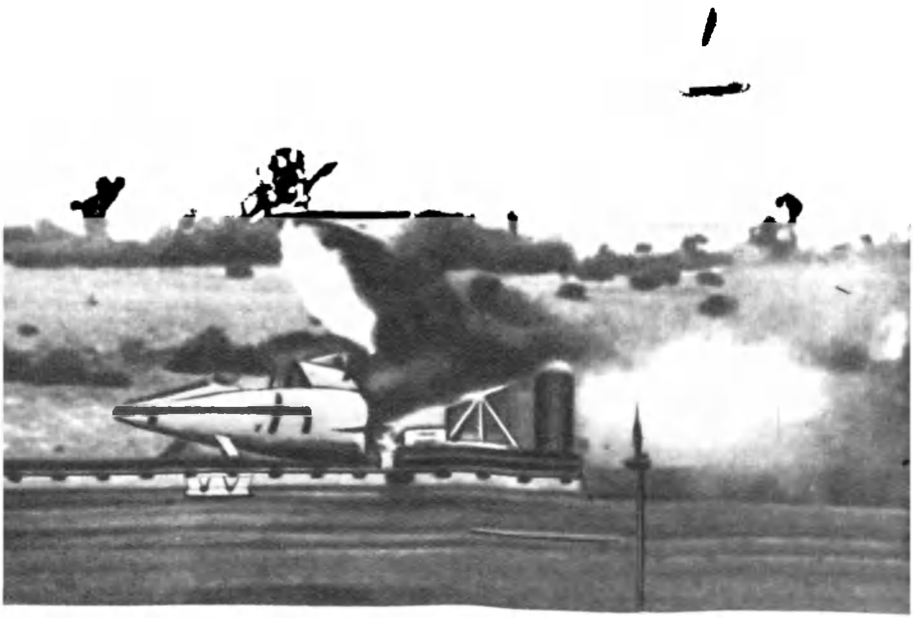
We all know a great deal about modern cinematography and filming methods. In imitative possibilities, cinema techniques quite resemble those of photography: it uses the same materials, and the optics of cine cameras practically does not differ from that employed in photographic cameras. But cinematography possesses one more very valuable property—that of being able to record movement, breaking it down into minute consecutive stages. The wide use of

cinematography in science and engineering is wholly due to its ability to divide a continuous motion into a multitude of consecutive and immobile images recorded very accurately on film. This ability to stop motion or slow it down and show it step by step is especially valuable in our time of high speeds, when most processes investigated by science and employed by engineering have been speeded up to such an extent that man can no longer follow them with his own sense organs.

Here is an example of such a process.

It is known that in case of an accident in the air the crew abandon their aeroplane and save themselves with parachutes. In propeller-driven aircraft the crew always have at least a little time in which to leave the falling plane and jump to safety. Besides, the speed of such planes is not very high, so that the impact of the oncoming air is not much of an obstacle to saving the crew. But parachute jumping from a modern jet plane is quite a different thing. Bailing out from such a plane is not so easy. In case of accident, special life-saving devices are provided. These are ejection seats, one for each member of the crew. In case of necessity these seats are instantly ejected and overcome the air impact at a very great velocity, carrying their passenger to a safe distance, after which the parachute takes over.

Men's lives depend on the reliability of such seats, the efficiency of their operation and the stability of their position in a stream of air. And that is why aircraft designers keep constantly perfecting ejection seats, developing more and more new types. However, before recommending even a very good novelty it has to be mastered and thoroughly tested from all aspects. For only experiment is able to give exact information as to the quality and reliability of their operation. Mathematical calculations are unfortunately not so accurate in this case, that they could be relied upon without practical verification. But how is such a seat to be tested? You cannot just install it in an aeroplane and trigger it off into the air with a man sitting in it. Before doing that you have to be absolutely sure that the danger incurred is a minimum. Therefore, the design and reliability of operation of the ejection seat are mastered first on the



The cart is raced along a railway track by a jet engine at an immense speed. It has an aeroplane cabin installed in its front part. At a command from the tester the cap comes off (top, right), the charge of the ejection seat explodes and the seat flies out of the cabin. The seat has a dummy in it. In the picture, the seat after leaving the cabin retains its upright position in the air. These tests were successful.

ground. One of the photographs of such a test is reproduced here. As you see, the conditions under which they are performed are very close to the actual conditions.

A cart propelled by a jet engine races down a railway track at a tremendous speed. It carries an exact copy of the cabin of the new aeroplane with the ejection mechanism to be tested. You can see a man sitting in the seat that hovers over the cart. But there is no need for alarm: it is not a live man, but a dummy, a very accurate copy of a flyer in a flying suit. The dummy's weight, size, and the position of its centre of gravity are exactly the same as a man's. And owing to all this, the behaviour of the ejection mechanism and the seat itself will be the same as in real life. In case of accident everything will happen in exactly

the same way: the top cover comes off the cabin and rises above it, and then the seat is shot out by powder charges. And if the seat is designed properly, it will be stable in the air.

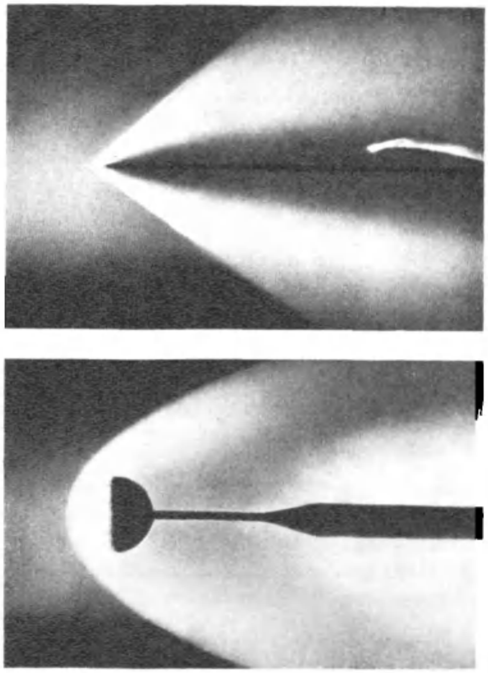
But all this can be found out only by photographing the test as it is performed, because the eye is unable to catch all these stages. Conventional cine cameras cannot be used to photograph very rapid processes; this is done with special high-speed cameras capable of taking many thousands of frames per second.

Another example of the use of high-speed photography also relates mainly to aircraft engineering. But this time it has to do with testing bodies of various shapes in supersonic wind tunnels. In such tests engineers want to find out the shape of the air streamlines when passing around the bodies tested. By studying these streamlines they can find the best shapes for aeroplanes, rockets, missiles, offering the least resistance as they move through the air.

The high speed of the processes involved is not the only difficulty of this task. A no less complicating factor is the fact that air is transparent, so that no waves or eddies can be seen in it by ordinary means. To overcome this difficulty, special light sources are employed, which send their rays through the air stream, and special methods of photographing are used. Only after this does what is invisible to the naked eye become readily distinguishable in the photographs taken.

At present high-speed cameras which can make 100 thousand exposures per second are not such a great rarety, and they are used frequently for various purposes. This is quite a miracle, if we stop to think about it. One second is stretched out into a whole 24-hour day! Eruptive processes, lightning flashes and other electrical discharges, collisions between swiftly moving bodies, the flight of a shell—all this can now be recorded on photographs which can bring out the minutest stages, the minutest changes in a process which begins and stops in the course of thousandths of a second.

But cinematography is not only able to stretch time out, it can just as well do the opposite: compress days and months into seconds. This property is utilized to investigate



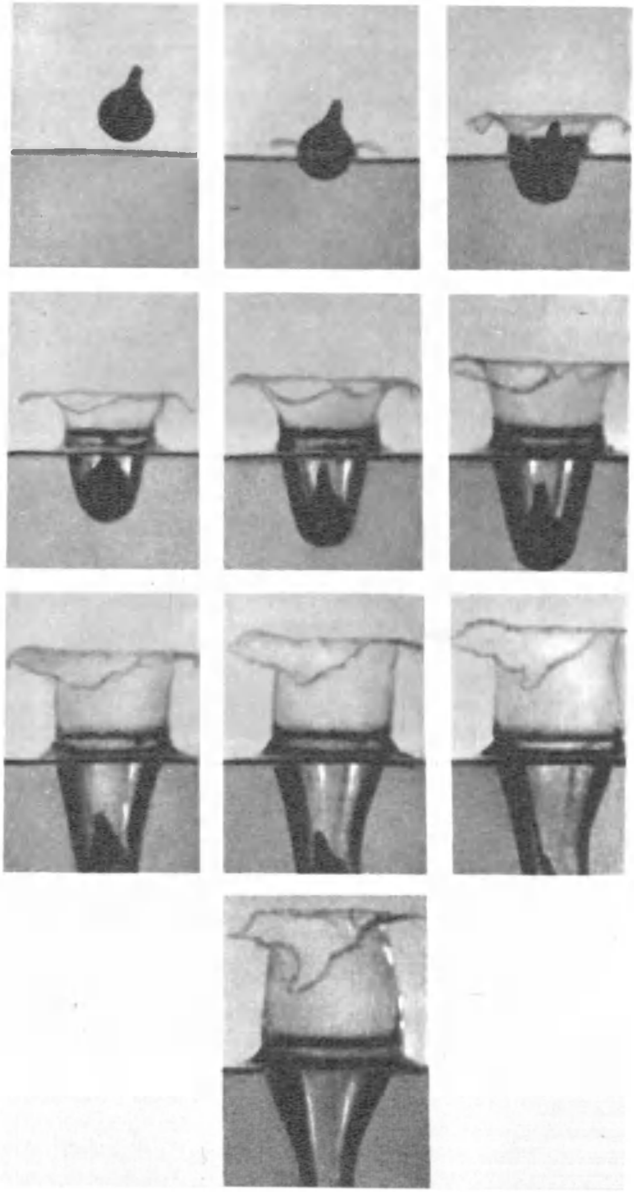
Photograph of gases streamlining an obstacle.

very slow processes, when the eye is not able to notice the minute and slow changes.

Look at the face of your watch—the minute and hour hands seem to be quite immobile. And although we know that they are rotating, we are unable to notice their movement. For the same reason it is impossible to observe the growth of trees, flowers, cerials, the course of certain chemical processes, say, crystallization and many, many others.

This is where extra-low speed shooting comes to the rescue.

Suppose we want to take a cinema film of the development of some plant. We place the pot in which we have planted the young shoot or even the seed in front of an



Consecutive photographs of a body falling into a liquid, taken with a high-speed camera.

automatic camera which takes, say, ten shots per 24 hours. In order to maintain constant conditions of illumination when photographing, the plant is illuminated by a bright flash lamp at the moment of each exposure. If such cinema observation of the plant is carried on for two months, we get 600 frames, which record the minutest changes in development of the plant in the course of 60 days. Using a conventional cinema projector, we see how the stem reaches out towards the light, how the leaves develop, the buds swell and the flowers open up, all in the course of 25 or 30 seconds.

A Cinematograph Gun

Down the air-strip, running slower and slower, comes a plane just safely landed. It is a machine of a new type, just back from its first test flight. The plane comes to a stop, turns around, and a few minutes later taxies up to the hangar. The engines go dead, and the pilot comes down from his cabin on to the ground. And immediately, without giving him a chance to recover his breath, agitated men begin to fire questions at him from all sides. These are the designers. They have spent many months, and maybe years, in working on the aeroplane that has just landed, and are naturally all eager to know how it behaved in the air: whether it responded well to the controls, whether it climbed fast enough, whether anything unforeseen happened. Each of the designers knows that scores, even hundreds, of various recording instruments have been closely following the behaviour of the aeroplane in the air, and that their readings will be able to tell them almost everything they want to know. But only the test flyer, the fearless friend and counsellor of the aircraft designers can give them the most important, the most valuable information.

Nowadays, more and more often various kinds of unmanned flying machines take off from the ground: rockets, man-made satellites, automatic interplanetary stations, experimental space ships. They no longer have any test-flyer on board. Their flight is controlled and recorded only by instrumentation. The number of instruments is large, and they give the designers very valuable information. But this

This device resembling a large-calibre siege mortar is actually nothing but one of the best cinetheodolites. It is operated by two men.

is not enough. It is necessary to see how the rocket or satellite behaves in flight. And not only see, but record what was seen, and establish how accurately they kept to the set path or carried out the planned manoeuvre.

But how is all this to be seen? Far from standing still, the rocket is speeding scores and even hundreds of kilometres away from the observers. And still, though it was an extraordinarily difficult task, this problem was solved by modern applied cinematography. Of course, the cine cameras employed for these purposes are far removed from the conventional type. When you see a photograph of one, you can hardly tell right off what it is.

The cinema camera shown in the picture is one of the best in its line. In fair weather it can photograph objects

hundreds of kilometres away. This accounts for its enormous objective resembling a large-calibre siege mortar. The design of these cameras is very interesting. It resembles a gun not only in the "barrel" of its huge objective. The mechanical part of the unit makes it still more like an anti-aircraft gun. To enable continuous observation of the rocket as it speeds through the sky, the unit is installed on a heavy revolving steel carriage. The direction of the lens can be rotated through 360° horizontally and 90° vertically. Therefore, no matter how the object moves, the lens can always be trained on it. This is done by two operators, each using a separate telescope sight. One of them trains the camera horizontally. It is his duty to keep the image of the object exactly at the intersection of the cross-hairs of his sight, so that it should not deviate left or right. The second operator, watching through his sight, also keeps the target at the intersection, so that it should not deviate up or down.

Each operator controls the revolution of the unit by means of a handwheel, just like when training an anti-aircraft gun. But though the unit is heavy and clumsy, this requires no effort. It is not muscle-power that moves it but electric motors. The handwheels only transmit control commands to special electronic circuits which make the motor rotate at a higher or lower speed or reverse its direction of rotation. It is enough to turn the "horizontal" control wheel ever so little from its neutral position, for the entire heavy and clumsy unit to begin revolving slowly and very, very smoothly. The more the handwheel is turned, the quicker the unit revolves. The same happens when the "elevation" control wheel is turned. In this case the whole unit does not revolve, but only the camera with its lens and sights.

The massive steel carriage and the complex control system are necessary to ensure exceedingly high accuracy of training of the camera. The accuracy of training is necessary, in its turn, to obtain correct data concerning the bearings of the object. They can be calculated only if the object is photographed simultaneously by two or three such units separated by a sufficiently large and exactly known distance. In this case calculation of the bearings reduces

to finding the lengths of the sides of triangles given their bases (distances between the units) and angles.

Cinema cameras by which the angle of training on the object can be exactly determined are called cinetheodolites. This name is due to the fact that they essentially make it possible to solve the same problems as are solved in surveying by means of conventional theodolites.

Each frame taken by the cinetheodolite contains, besides the image of the cross-hairs and the target, figures indicating the angles of horizontal and vertical training on the object. Besides, the picture also bears marks of a uniform time service, by which frames exposed at the same moment of time by each of a group of cinetheodolites can be matched. The uniform time service synchronizes the shooting, as they say. All the cinetheodolites are connected up by wire lines or by radio and photograph the rocket or other object at the same moments of time.

Cinetheodolites have been very useful in developing and testing rockets. Possibly, in looking through magazines, you have come across photographs of rockets with dark and light squares or zigzags painted on them. These ornaments are not the whim of the artist. Such design facilitates observing the rocket in its flight, makes it possible to determine whether the rocket is rotating about its longitudinal axis.

Each test flight of a rocket is photographed from the moment of its launching and as long as possible. It is too bad, though, that today's cinetheodolites still defy all efforts of designers to make them work in cloudy weather, or even through a heavy haze. Even the movements of warm air currents are just as much an obstacle to their operation as to astronomical observations.

LIGHT AND ELECTRONICS

There was a time, very long ago, when everything man made or procured was literally the fruit of his handiwork, his hands being aided only by primitive stone implements. The hand was at the same time his most perfect tool and the only mover actuating his stone instruments of labour; a no less important part was played by the human sense organs and brain. The sense organs inspected the work, noticed successes and failures and communicated their findings to the brain. On the basis of these reports the brain checked whether the result corresponded to the idea it had itself made up, drew conclusions and sent the necessary commands to the main executor—the hand, which governed the stone implements. That period, which lasted for hundreds of centuries, is referred to as the Stone Age.

Thousands of years passed, and stone instruments of labour gave way to metal ones. But though the instruments of labour had become much better, the main mover, the principal source of power which breathed life into these instruments, remained the muscular power of man's hand. Of course, man found himself helpers, animals. They helped him to carry loads and to move quickly over great distances.

Metal implements lasted longer than stone ones, were

more convenient to handle, and helped to improve the quality and workmanship of the products made. But this improvement could not be effected by merely arming the hand with more efficient implements. It was necessary as well to improve the means of inspecting the production process, to invent various devices to aid the imperfect human senses in obtaining higher accuracy of inspection. And such devices were invented. Thus appeared the plumb-line, the rule, the balance, protractors and many other simple measuring devices.

A new age came in after people learned to utilize the energy of the wind and water. This was an enormous achievement. For the first time in history the muscular power of man and animals was substituted in many fields by the power of the wind and of water. It was much greater and enabled people to begin making things of such kinds and in such quantities, of which they could not even have dreamed formerly. But as in the previous epoch, the progress of engineering could not have been very great if it had been limited solely to the mastery of new kinds of energy. Simultaneously with this, man's instruments of labour improved, and the possibilities of his sense organs were multiplied being equipped with new, still better control instruments. It was in the age of wind and water power that such important instruments as the lens, the clock, the telescope, the microscope, the compass were invented. This age covered many centuries, beginning approximately with the downfall of the Roman Empire, and lasting until the first industrial revolution which started in the 60's of the XVIII century. During this period mankind went through feudalism and entered the stage of capitalist development.

The first industrial revolution began at a time when the march of science and industry had brought in very efficient instruments of labour and the first machines. However, it could not have occurred if wind and water power had remained the chief motive force for the new highly productive instruments of labour. And soon after there arose the need for a more perfect mover, that mover was invented. This was the steam engine, which ushered in the steam age.

Never before had man had so much power at his disposal. The new mover speeded up production processes still

more, raised the accuracy of manufacture and finish of the instruments and products of labour. The steam age is marked by other important inventions, too. And it was then that the first successful attempts were made to create devices that would liberate in the production process not only man's hands, not only his senses, but his brain as well.

The steam age lasted almost a hundred years. During this period the steam engine was the leading power at factories and plants, in mines and on railways. But long before this age was over a new kind of energy came into use in engineering—electricity. At first it was not known how to produce it in large quantities, and there was hardly enough to supply the new wonderful means of communication, the telegraph and telephone, which so greatly extended the possibilities of man's hearing. With the aid of electricity people could hear and carry on conversations over immense distances.

The end of the steam age is related to the time when inventors found methods of transforming steam power into electric power, when the electric generator and the electric motor were created. They became the forerunners of the age of steam and electricity. This happened between the 60's and 90's of last century.

The electric motor crowded the steam engine out very quickly. Steam remained only at thermal power stations and at all units which could not be wired to power stations. That is why the steam engine, and later the steam turbine did not yield its place in transport. But after some time it was challenged by a new type of engine—the internal combustion engine.

And still, soon electricity had come in everywhere. It was the universal kind of power that not only gave life to all of industry, but enabled numerous different kinds of instruments to be made, which could serve as genuine artificial sense organs, greatly superior to those of man in accuracy and speed.

But no sooner had the age of steam and electricity come into its own, than mankind was granted a new boon, radio. And then came another—the electron valve.

The world was nearing a new industrial revolution. The

30's of our century saw the birth of the first two great offsprings of radio electronics—electronic television and radar. Both these inventions extended immeasurably the possibilities of man's principal sense—vision. But electrical engineering would not let electronics outstrip it. It became the forefather of a new field of engineering—electrical automation. If we disregard the comparatively few successful attempts to build the simplest automations based on mechanical devices, electrical automation was the field of engineering that succeeded in substituting the human brain on a rather large scale, at least in the simplest cases.

Automation came to life not just as a whim of inventors. Its appearance and wide application were dictated by the new conditions of development of engineering. Under these conditions the human senses and brain were no longer able to cope with the tasks set before them. Automation began to develop quickly especially during the war. It was then that the means and methods of electronics came to be used extensively for making automatic devices.

At the very end of the war engineering made a new decisive stride forward: the electronic computer came into existence, this being the first machine possessing the faculty of highly organized logical operations.

And at about the same time the peoples of the world learned of the terrible atomic bombardment of two Japanese cities. A new kind of energy, the vast supplies of which make it possible to build a beautiful future society, was criminally used to kill people. This barbarous act struck horror into all mankind, and many sincerely believed that the discovery of methods of utilizing atomic energy could bring nothing but misfortune in the future too.

Those people were wrong. The Soviet Union showed that the atom can be utilized for peaceful purposes as well. In 1954 the world's first atomic power station near Moscow began to supply electricity to industrial enterprises.

This extra-brief, incomplete and rather conventional review of the march of engineering suggests a very important conclusion, consisting in the following. Engineering progressed along several roads, of which three stand out the most distinctly. The first was the substitution of the machine-mover for the human hand and the improvement

of movers as new sources of energy were mastered. The second was the replacement of the human senses by special instruments and the improvement of these instruments as new kinds of energy were mastered. And the third is the liberation of man's brain from the sphere of production processes by contrivances possessing more or less the faculty of performing logical operations and giving out directive commands. These contrivances are now often called thinking machines.

We owe the major achievements attained in the field of creating artificial sense organs and thinking machines. to electronics. Essentially, electronics is the branch of engineering which creates such devices and machines.

Much has been said in this book devoted to light and vision about various devices which have greatly extended the possibilities of our principal sense. But nothing has as yet been said about what electronics has done in this field. And if polished pieces of glass or thin glass plates coated with photographic emulsions helped man to achieve so much, then what miracles must electronics do?

It is these miracles that we are coming to now.

Electronic Cells

In nature everything develops from the simple to the complex. And, of course, the eye did not become what it is all at once. It had to go through a very long period of evolution before it reached its present high state of perfection.

Where did this period begin?

Modern science does not yet know the exact answer to this question. But all the data at its disposal point to the fact that even the simplest organisms of the distant past possessed the faculty of sensing various external influences. At first the cells contained in these organisms all reacted equally (and, therefore, badly) to various kinds of irritants. In the course of evolution special cells began to separate from the sum total of them, which were especially susceptible to external influences. They became the rudiments of the sense organs. These cells underwent further changes

and gradually began to specialize among themselves. Some of them became more susceptible to chemical influences (smell and taste), others—to mechanical (hearing and feeling), while still others became especially sensitive to the action of light.

We know that the faculty of seeing is the gift of animals in the higher stages of development. But the ability to sense light and to determine the direction towards the light source is found even in very primitive live organisms and plants. Remember, for instance, how the sunflower turns with the Sun; recall the leaves of various plants, which also change their position with the movement of our diurnal luminary. This shows that they also possess certain organs which sense light and the direction of its rays.

And this is actually so. For example, each maple leaf has on it up to 15 thousand specialized cleverly devised light-sensitive cells. Their surface, which comes out on the outer side of the leaf, has a convex lenticular shape, and they contain a transparent substance inside. Solar light incident on such a cell is focussed on its back wall. The point where the rays converge shifts when the sun moves. And the movement of this point makes the light-sensitive cell produce signals which cause the leaf to rotate with respect to the Sun so as to bring the focal point back to its original position.

Cells of a similar kind are found in many plants and simplest animals. They are primitive light-sensitive organs.

In science and engineering, like in nature, everything develops from the simple to the complex. And, naturally, the first artificial organ of vision was very simple. The first artificial light-sensitive "cell", electronic "cone", was the photoelectric cell. It is a fused glass bulb with electrodes inside. How such a photocell works, and what phenomenon its working principle is based on, we already know.

Now we shall see how engineering utilized this primitive electronic sight organ and perfected it. The photocell conducts current when a ray of light falls on the photocathode. The more intense the light, the higher the current. This property of photocells has made it possible to employ them in a great variety of cases.

For example, the conveyor of an assembly line carries the products from one working place to the next, and gradually the products acquire a more and more finished appearance. Finally the last operation is completed, and the finished product comes off the conveyor. And at that very moment it crosses a ray of light directed at a photoelectric cell. As the ray is broken, the current stops flowing through the cell and an electronic circuit connected to it sends a command to an electromagnetic relay. The latter operates and turns the meter drum one division up. It is very important that the meter may be installed at any desired distance from the conveyor and be connected to the photocell either by wires or by radio.

Such a meter can be employed not only in industry. It can be installed anywhere, say, at the entrance doors to an exhibition room or museum, and it will determine the exact number of visitors. A device consisting of a photocell, an electronic amplifier and an electromagnetic relay is often used to guard the life and health of workers. It saves the man from maiming by stopping the machine or moving out a protective shield if the worker's hands or he himself move into the danger zone.

A burglar who succeeds in breaking into a shop, warehouse or bank where all the entrances and exits are guarded by photocells, is not likely to get out again. The moment he crosses at least one of the beams, the alarm signal goes off, emergency locks spring into place and the intruder is caught beyond escape. Is it possible to fool such a guard, to get past it unnoticed, without crossing a light ray? No. In contrast to the rods and cones of the eye, the electronic cell is capable of perceiving invisible ultraviolet or infrared rays. And he who tries to fool such an invisible guard would never know he has crossed a "black" light beam.

In speaking of recorded light and movements we did not mention that in cinema light is used also to record sound. Each sound motion picture film has a special image along its edge, called a sound track, on which the sound is recorded as an alternation of sections of different transparency or light transmittance. Only a photocell can read such a record. As the film with the sound track passes

through the beam of a special lamp of strictly constant brightness, the intensity of the light incident on the photocell keeps changing continuously. This causes the current flowing through the cell to vary in proportion with the light intensity. The electrical signals thus obtained are sent from the photocell to an electronic amplifier which raises their power to a value sufficiently high for the loudspeakers installed in the hall of the cinema theatre to emit sounds of the required loudness.

Numerous very useful instruments can be made with the aid of the simplest photoelectric cell. Still, it is far from being ideal. Its chief shortcoming is low sensitivity. It can work only if illuminated by a very strong light. But even then the intensity of the current flowing through the photocell is exceedingly small. The photoelectric cell is much inferior to the eye in sensitivity—it is not only worse than the rods, but worse than the cones as well. The photocell must always be used in conjunction with an electronic amplifier, and this is expensive and inconvenient.

The Multiplication Principle

Scientists and engineers strived to eliminate this shortcoming of the photoelectric cell which kept them from applying it in many very important devices. And they sought ways to raise its sensitivity and to increase its operating currents. To solve this problem they looked for metals and compounds which when incorporated in photocathodes would make it possible to increase the number of electrons emitted by the same amount of photons incident on the photocathode. This is a correct way, but the gain to be had by it is not so great. The laws of nature establish a natural limit here. As we remember, the laws of photoeffect show that even in the ideal case each photon (if, besides, it possesses sufficient energy) can knock out only one electron. At present photocathodes have been made which emit one electron per every five incident photons. Of course, those photons which are inherently unable to knock electrons out of the material in question are not taken into account.

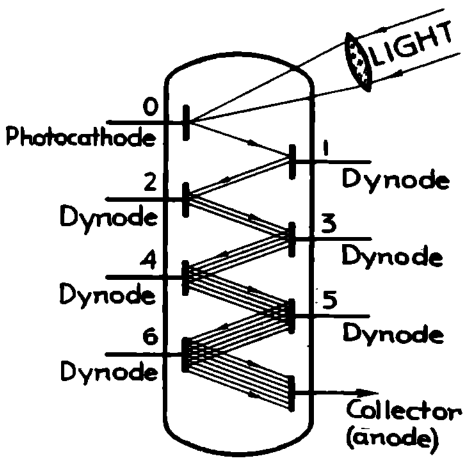


Diagram of a photomultiplier. The light incident on the photocathode 0 *knocks electrons out of it. Voltage is fed to the electrodes* 1, 2, 3, 4, 5, 6 *and to the collector, the voltage applied to each subsequent electrode being higher than to the previous one.*

This is an excellent result. But scientists have found another more radical method of raising the sensitivity and the operating current. The first to use it and to obtain good results was the Soviet scientist Kubetsky. The new type of photocell invented by Kubetsky is called the photomultiplier.

If a sufficiently large energy and, therefore, a sufficiently high velocity, is imparted to the electron emitted from the photocathode and it is directed at a metal plate, the electron may knock other electrons out of the plate. It is very important that the metal for the plate, its shape and the velocity of the primary electron can be selected such that the latter will knock out not one, but several secondary electrons from it, say, five or six. In their turn, these electrons can also be speeded up and directed at another similar plate. Then 36 electrons can be knocked out of it. If this operation is repeated we can knock 216 electrons out of the third plate, 1,296 out of the fourth, etc.

In creating the photomultiplier Kubetsky took advantage of this phenomenon. He speeded up the first electrons

knocked out by the photons (for which reason they are often called photoelectrons) in an electrostatic field, made them impinge on a metal electrode (called the dynode) and knock out secondary electrons. The latter were also speeded up and directed at the next dynode. This process was repeated many times, and the number of electrons grew from dynode to dynode like a snow avalanche. The last electrode, which essentially played the part of the anode in an ordinary photocell, thus received thousands and even millions of secondary electrons instead of the single photoelectron. In Kubetsky's apparatus the photoelectrons multiplied, as it were, according to the law of geometrical progression. That is why the apparatus was called a photomultiplier. With it, instead of the one electron per five photons, as before, we can obtain up to a million secondary electrons per photon.

And still, only in a few cases can the best photomultipliers compare in sensitivity with an eye fully adapted to the dark. In these cases certain electronic circuits with photomultipliers may be sensitive to light fluxes containing a few dozen photons per second. But to achieve this the photocathode and dynodes must be cooled to minus 100°C and lower.

And here is why.

Electrons can acquire sufficient velocity to depart from the photocathode only if sufficient energy is imparted to them. They can receive this energy not only from photons, but also if the photocathode is heated. When it is heated the energy of the electrons may become sufficiently high for them to fly out of the photocathode. In electron valves the cathode (in this case it is called a thermocathode) is heated purposely to produce free electrons, which are often known as thermal electrons. True, for the thermocathode to emit as many electrons as possible, it is heated to several hundred degrees and more.

The emission of thermal electrons by the cathode of an electron valve is decidedly a useful phenomenon. But it becomes very harmful in photocells and especially in sensitive photomultipliers. Even the negligible amount of thermal electrons that fly out of the photocathode at room temperature is liable to interfere with the normal operation

of the device. It must be remembered that the current caused by thermal electrons is independent of the light signals coming to the photocathode, but it is registered by the meters connected to the photomultiplier just as the current caused by the photoeffect. In other words, the thermal electrons in the photomultiplier cause false signals. If these signals are large they interfere with the normal operation of the device, may be misleading and even mask the wanted signals if the latter are weak.

False signals due to thermal electrons exist always and uninterruptedly. If we fed them to earphones or to a loudspeaker we should hear a characteristic continuous hissing or noise, as it is called, against the background of which only sufficiently strong wanted signals could be heard. It is this noise, present always not only in photocells and photomultipliers, but in all electronic devices, that makes it impossible to discern very weak desired signals and prevents us from getting the maximum sensitivity out of photomultipliers.

All available means are used to combat noises in electronics. The less the noise, the weaker the signals that can be registered by the apparatus, the fewer false (also called parasitic) signals there will be. That is why photomultipliers are cooled to such a low temperature. This greatly reduces the number of thermal electrons emitted from the photocathode.

Photomultipliers are widely used in science and engineering. Many optical instruments in which the only sensitive element was formerly the eye are now made with photomultipliers. They have proved to be the artificial sense organs capable of replacing the human eye, and have made it possible to carry out much more accurate quantitative measurements. Besides, and this is very important, the electrical signals they put out can be fed into electronic thinking machines and thus make measurements automatically.

Photomultipliers are employed extensively in astronomy for studying the spectra of stars and for measuring their brightness. In physics photomultipliers are used to make very sensitive scintillation counters, with which negligible levels of radioactivity can be determined.

Light signalization has been in use for a very long time in the merchant fleet and in the navy. There are two kinds. One employs conventional combinations of coloured lights, the other is based on light flashes. Using the Morse code and signal lamps conversations can be carried on at very large distances. But very often those who carry on such conversations wish to keep secret not only their content, but even the very fact that such a conversation is going on. To maintain such secrecy the navy used Ratière lanterns which gave a very narrow beam, invisible if viewed sideways. But even they did not guarantee complete secrecy.

Before World War II light communications based on invisible infrared rays began to be used extensively. The transmitters were special spotlights. The light sources in them could be ordinary powerful incandescent lamps, but the front of the spotlight was covered with special filters which let only infrared rays through. The signals of such a transmitter were received by a photocell placed in the focus of a lens which was also covered by an infrared filter. The range of the light telegraph was very limited. It was increased successfully only after the invention of photomultipliers.

At about the same time the light telephone was invented. The transmitter of this telephone was, as before, a spotlight with an infrared light filter. But a special gas-discharge lamp was installed in it instead of the ordinary incandescent lamp. Lamps of this kind change their brightness in time with the change in value of the voltage fed to them.

The lamp of the light telephone was connected to the output of a powerful electronic amplifier. The amplifier input was wired to a microphone which transformed speech into electrical vibrations. They were amplified by the amplifier and varied the intensity of the light emitted by the gas-discharge lamp. At the receiving end the pulsating light was picked up by a photomultiplier and retransformed into electrical vibrations. The latter were amplified, like in sound pictures, and were fed to earphones or a loudspeaker. In the last war light telephones of this kind were used by many armies.

You have doubtlessly heard of radar. These highly perfect devices enable man to detect objects in the air, on the ground, and on the surface of water at any time of day or night and under any meteorological conditions. Neither snow, rain, nor fog are obstacles to radar. This remarkable property is due to the fact that the radio waves on which radar works are much longer than the longest infrared waves. And the greater the wave-length of electromagnetic vibrations, the less such phenomena as snow, rain or fog can hinder them.

Another very important property of radar is that it enables the distance to objects to be measured very accurately. The principle of measuring distances by radar is very simple. It consists in measuring the time interval that elapses between the emission of a very short packet or "flash" of radio waves and the return of the radio waves after reflection by the object. Knowing their rate of propagation and the time it took the waves to travel to the object and back, the distance can be determined quite easily.

Light rangefinders are based on the same principle. A special undulating light source is placed in a projector where it emits exceedingly short light flashes of extremely high intensity. The ray of the projector is trained on the object, which reflects the light flash. A very small part of the light returns, and here it is picked up by a light receiver —a mirror- or lens-type object glass with a photomultiplier at its focus. The time between the emission of the flash and its return is measured by means of special electronic circuits of the same kind as in radar.

These rangefinders can be made so accurate that in some countries they are employed in geodesy. True, they cannot work even in a moderate mist, and clouds are an impassable obstacle to them, even if infrared rays are used. This is a very great shortcoming of light rangefinders, but it can be turned into an advantage. For example, a rangefinder can quickly and accurately determine the height of the lower edge of the clouds, which cannot be done by conventional radar. At present new wonderful light sources—lasers—are coming into use in rangefinders.

Sensitive Eyes

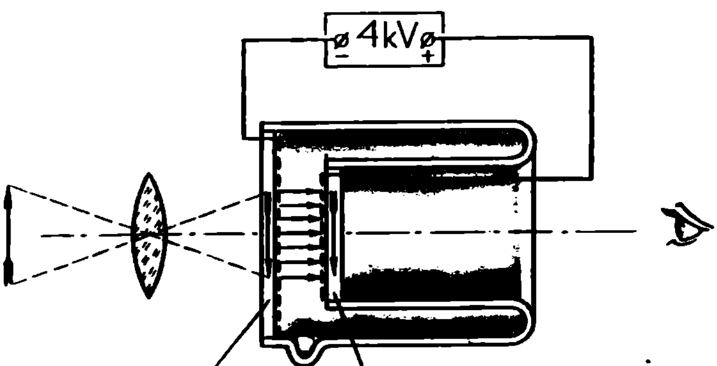
Thus, photocells and photomultipliers proved to be very useful instruments and have replaced the human eye in a number of cases. But this is possible only when it is required to register the presence or absence of light rays or obtain electrical signals proportional to the variation of the light intensity in time. Neither the photocell nor the photomultiplier can really see. They extend certain of the properties of vision, but they are not able to aid the eye like a microscope or telescope, a photographic or cine camera.

Is electronics generally able to cope with such a task?

It certainly is, and it is aided in this by the photoeffect. We shall now tell about one of the magic instruments created by electronics, which enables man to observe the invisible directly. This instrument is called the image converter.

A schematical diagram of the simplest converter is given below. It is evident that the converter is a glass bulb or cylinder resembling a drinking glass; not a simple one, but one with thick hollow walls and a double bottom.

Examine the drawing attentively and you will see that there is a photocathode (resembling that of a photomulti-



The first type of image converter.

plier) on the inside surface of the bottom of the larger glass. You will notice also that a layer of a luminophore is applied to the inner surface of the smaller glass, a luminophore being a specific powder capable of giving off light when bombarded by electrons. This luminophore forms a screen rather similar in properties to the screens of kinescopes for television receivers. Note that the positive pole of a high-voltage source is connected to the screen, and therefore the latter is at the same time an anode.

On the same drawing you see a schematic representation of the object, focussed on the photocathode. In accordance with the distribution of illumination over the object, different areas of the photocathode are illuminated differently, like any photographic plate. On the basis of Stoletov's law, each of the areas of the photocathode emits proportional quantities of electrons per unit time: the weakly illuminated areas emit few of them, and the strongly illuminated ones, many of them.

If a high voltage is applied the electrons will fly towards the screen, being speeded up on the way. What will be their paths? It appears, and this is very important for a transformer of this design, that each of the electrons will travel in a straight line perpendicular to the point of the photocathode from which it was emitted. And this means that each point of the photocathode is connected, as it were, by an invisible tube, with a corresponding point of the screen. And the electrons travel along these "tubes" without mixing.

This being the case, each point of the screen will glow with a brightness proportional to the quantity of electrons flying out of the opposite point of the photocathode. And, therefore, we see on the screen the same picture as is projected on the photocathode by the lens. It is drawn on the white screen by electrons. The quality of the image in modern image converters of much more complicated design, than that described, is very good. It is not much inferior to that of photographs obtained from negatives taken by a miniature camera, though the image sometimes becomes perceptibly worse towards the edges.

Some of our readers may doubt the usefulness of such conversion which has long since been mastered by photo-

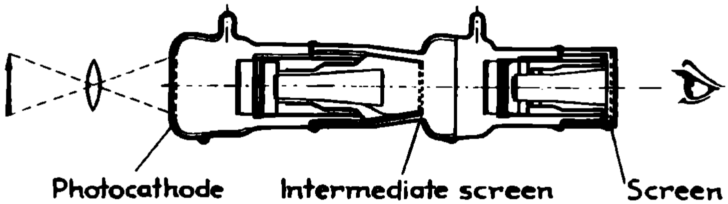


Diagram of a modern two-cascade image converter.

graphy. Indeed, photography can obtain images in infrared and ultraviolet rays. But think how much time we lose before the picture is ready to be examined! While the image converter shows the operator what is occurring at the moment of observation, and thus makes it possible to carry on active observation. And this means that, if necessary, the operator can intervene with what is happening and control the results of his intervention.

The makers of the image converter set themselves the task of furnishing the eye with a device which would make it possible to carry on active observation in the invisible rays of the spectrum. They meant to use primarily infrared rays for this purpose, because these rays are capable of penetrating a haze, and many objects, especially of military significance, themselves emit such rays intensively and therefore can be spotted if observed through an infrared converter.

However, as converters improved in quality, new wonderful properties were found in them. The most important of them is that the brightness of the image on the screen may be many scores of times higher than that of the object itself. In other words, image converters proved to be at the same time brightness amplifiers. An especially high amplification can be obtained by employing a cascade of amplifiers. The cascade principle is very simple and consists in that the brightness-amplified image is again projected from the converter screen on to the photocathode of a second converter, where it is again amplified. Thus, the image on the screen of the second converter is many times brighter than the brightness-amplified image obtained on the screen of the first converter. Such a cascade hook-up of

converters makes it possible to increase the brightness by as much as a thousand times.

And this means that the image converter makes it possible to see (and see well) in such utter darkness in which the eye of man, the cat, the badger and even the owl are quite helpless. The quality of the image, it is true, is spoiled a little in the cascade converter, its crispness becoming slightly worse. But if we take into account that so far it is the only instrument in the world surpassing the human eye in sensitivity, this decreased crispness can hardly be considered a decisive shortcoming.

The photomultiplier can be made highly sensitive only by greatly cooling it. The image converter must also be cooled, like the photomultiplier, if it is necessary to see very feebly illuminated objects. An uncooled converter cannot be much more sensitive than the eye. In this case strong disturbances, also called noises, though we do not hear them, will be perceptible on its screen. These noises resemble a snowfall, the snowflakes being the thicker, brighter and larger, the higher the working temperature of the converter. At room temperature the snowfall on the screen becomes a snow-storm and even a blizzard through which the image of weakly illuminated or small objects cannot be seen.

Image converters have military and peaceful uses. Primarily they are utilized in military engineering, for example, in infrared night sights. Still, the converter has also become a peacetime tool. It not only arms the soldier's eye, but helps to cure diseased eyes as well. Many substances, including live tissues, are transparent to infrared rays. One of these is the terrible white growth on the pupil called walleye. By means of the image converter the inside of the eye can easily be investigated, and a method of treatment decided upon.

Above we told of the "МИК-1" microscope, in which a converter is also employed. But this converter can be utilized successfully not only in microscopy; astronomists have also included the converter in the assortment of tools used for astronomical investigations. This time not so much for converting invisible rays into visible ones, as for increasing the luminance of faint stars.

Rifle with infrared projector and infrared sights. The box accommodates the power supply. Below—an infrared terrestrial telescope, the same sights and an infrared projector.

It is known that by photographing from the screen of an image converter the exposure time can be reduced by 50 to 100 times. In combination with a 500-centimetre telescope the image converter (in this case it would be more correct to call it an electronic light amplifier) will make it possible to see stars at distances that, without it, would be accessible only to a 50-metre telescope. In our days the construction of such a telescope is impossible. But even if we were able to make one it would be terribly expensive.

On the other hand the converter is a very cheap device, and with it the same results can be obtained.*

The image converter possesses one more wonderful property. If a special electrode is included in its design, we can block the way to electrons by applying a negative voltage to it, thus "locking" or closing the converter, as we do with light rays by means of photographic shutter. The very best shutters in present-day cameras cannot give a speed much higher than one thousandth of a second. Such a speed makes it possible to photograph a great deal, but in scientific photography speeds of millionths of a second are often required for studying very rapid processes. There is not a single mechanical shutter capable of opening and closing in such a short time. And this is where electronic shutters—image converters—come to the rescue.

The Fate of the Lost Photons

When reading about the photoeffect you probably wondered why not every photon possessing the required amount of energy knocked out an electron, and doubtlessly tried to guess what happened to the photons which arrived at the photocathode and remained in it without giving any useful result.

The questions can hardly be answered in brief. Therefore, those who wish to get a better understanding are referred to other books. Here, we shall confine ourselves to a very short and rather tentative explanation of this fact. It reduces to mentioning two important circumstances. The first is that some of the electrons torn out by the photons collide with other free electrons as they move through the crystal lattice of the substance constituting the photocathode. On colliding they yield part of their energy, and that left is no longer sufficient to allow them to leave the photocathode. Another reason is that the photons do not always give their energy away to free electrons. They sometimes

*Unless, of course, we take into account that the resolving power of a 50-metre telescope would be much higher, because the diffraction effect in it would be lower.

yield it to electrons bound to atoms. Far from all photons possess enough energy to tear out such electrons.

It would seem that one must reconcile oneself to such losses. But scientists have found methods of utilizing the photons that were formerly thought irretrievably lost. After discovering these methods they made photocells of an entirely new type. They are called photo-conductive cells.

This name is self-explanatory. The word "photo-conductive" shows that in such photocells the passage of current is not due to electrons that have left the surface of the irradiated substance, but to those which after receiving energy from the photons only left their atomic orbits and began to travel freely in the space of the crystal lattice. Less energy is needed to knock an electron out of its atomic orbit than to make it leave the surface of the irradiated substance altogether. That is just why the new type of photocell could be made more sensitive. In these photocells almost each photon which has a sufficiently high energy will liberate an electron and will enable it to carry a charge, that is, to conduct current. It is no less important that the required energy of the photons may be less in a photoconductive cell, and therefore the red boundary of these cells extends to much longer waves.

The new-type photocells have an entirely different design and are much simpler than the previous ones. They consist of a small piece of a specific substance mounted in a setting. Metal contacts—leads—are fitted snugly to its ends. The outer surface presented to the light is the working surface on which the light rays are trained.

When such a photocell is in the dark there are very few free electrons in the space of the crystal lattice. In this case they can be freed from the atoms only by heating. But when light rays fall on the working surface a large number of free electrons appear in the crystal lattice of the substance, and the higher the intensity of the incident light, the more electrons there will be. They travel chaotically through the space of the lattice in all directions. But the average number of electrons travelling, say, to the left at any given moment is equal to the number of them travelling to the right. Therefore, there will be no current in the photocell even if we short-circuit its leads. But if we

connect a source of electric current to the leads, the movement of the electrons will very quickly become orderly. Most of the electrons begin to move in one direction: from the lead connected to the negative pole to that connected to the positive one. Such an orderly movement of electrons is electric current. The more intense the incident light, the more electrons are liberated and the greater the current that flows.

These photocells have an important distinctive feature. It consists in the fact that the current flowing through them at constant illumination varies with the voltage of the source, obeying Ohm's Law. In other words, under unvarying illumination a photo-conductive cell behaves like an ordinary resistor. Owing to this property photocells of this kind are now sometimes called photoresistors. Another reason for this name is that in appearance they actually bear a great resemblance to resistors, the commonest elements of radio electronics.

We shall also use this name, which is the more convenient that it emphasizes the difference between photo-emissive and photo-conductive cells and makes it easier to avoid confusion.

Photoresistors are made of a special group of materials known as semi-conductors. At present photoresistors are most often made of lead sulphide, antimony trisulphide, lead telluride, cadmium sulphide and of certain chemical compounds containing selenium.

Present-day photoresistors are highly sensitive. It is no less important that with sufficiently intensive illumination they can allow a comparatively large current to pass into the outer circuit. This means that they can often be employed without any additional electronic amplifiers. Thus, the circuit of a simple counter, which formerly required the use of an amplifier together with the photocell, can now be made up of only a photoresistor, a battery and an electromagnetic relay.

Photoresistors also have their disadvantages. The main one is that they are inert, that is, are sufficiently sensitive and conduct their normal working current only if the intensity of the incident light does not vary at all in time, or varies comparatively slowly. But if it pulsates at a high

frequency or comes in the form of a number of successive short flashes, the photoresistor is unable to react to such rapid changes in illumination. In this sense the photoresistor resembles the eye, which is also unable to react to flashes that follow each other in rapid succession. As a rule, the inertia of a photoresistor is the greater, the higher its sensitivity.

Photo-emissive cells and photomultipliers do not have this shortcoming. They respond practically instantaneously to each change in light flux, even if it is very short-lived, very rapid. This makes photomultipliers eligible for use in particle counters and rangefinders, where the duration of the light flashes amounts to millionths of a second, and in light telephony where the light pulsates at a high frequency.

The first photoresistors more or less suitable for technical use appeared just before World War II. During the war years German specialists improved them somewhat. But only ten years have passed since photoresistors were developed to such a state of perfection that at present many important devices would be unimaginable without them.

New Roads

The scientists and engineers of many countries, who devoted their efforts to the development of various light receivers, did not rest on their achievements, and during the past few years new striking results have been accomplished.

The first successes were achieved by the makers of devices greatly resembling photoresistors, known as phototransistors. Photodiodes (devices with two electrodes) and phototriodes (with three electrodes) began to be made of two of the most important semi-conducting materials—germanium and silicon, the materials of which all other types of transistors are made.

Photodiodes and phototriodes proved to be even smaller in size than photoresistors, but they possess really marvellous properties. Photodiodes are inferior in sensitivity only to the best types of photoresistors, but are much superior

to them in promptness of operation. Their inertia is so low that even if the intensity of the light varies at a frequency of 100 or 200 thousand cycles per second, or if the flashes last for only hundred-thousandths of a second, they hardly lose in sensitivity and continue to produce signals of sufficiently high value. But this is only a beginning; in the future photodiodes can be considerably improved.

A photodiode can pass only comparatively small currents. But the phototriode is not inferior, even superior, in this respect, to photoresistors. In sensitivity some types of phototriodes are catching up with photomultipliers. Not all phototriodes have low inertia as yet, but a great deal is being done in this direction, and it has been reported that certain types of phototriodes can react to light pulsating at a frequency of tens of millions of cycles per second and to flashes which last only one ten-millionth of a second. Such phototriodes are quite suitable for use in rangefinders.

There is one more important advantage of photodiodes and phototriodes that is worthy of mention. It consists in the fact that they are capable of operating over a very wide range of illuminations without injury and without lowering their properties: from twilight to illumination by direct sunlight. In this respect they are hardly inferior to the human eye and considerably superior to photomultipliers. The latter cannot withstand high illuminations, and when exposed to intense light, highly sensitive photomultipliers fail immediately. If we add that phototriodes and photodiodes are very small in size, much stronger and immeasurably simpler in operation, it will easily be appreciated that they will find wide application in the near future.

The spectral characteristics of photodiodes and phototriodes depends on the material of which they are made. When germanium is used the red boundary of sensitivity is as high as 1.6 or 1.7 microns, that is, is in the infrared region. Silicon photodiodes and phototriodes have a high sensitivity only in the visible light range.

The spectral response characteristic of light receivers is a very important parameter of these units. On it depends their applicability for particular purposes. Work is being carried on at present with a view to expanding the boundaries of response, and especially to extending them into

the infrared region. The "champions" so far are photoresistors made of lead sulphide, lead telluride and compounds of selenium and lead. The red boundary of such photoresistors is at wave-lengths of from 3 to 5 microns.

But this is far from the limit. At present many kinds of new materials with wonderful properties are being investigated in laboratories all over the world. Special technical periodicals more and more often carry articles and reports of new tests and new experimental photoresistors whose properties greatly outstrip those of photoresistors now used in engineering practice. The most promising of them are photoresistors made of germanium alloyed with gold and of indium antimonide. Both of these materials can be made into very sensitive light receivers with a red sensitivity boundary at 7.5 and even 10 microns. It is worth mentioning that waves 10 microns long are emitted intensively by bodies at a temperature of only plus 15 degrees Celsius. The inertia of such photoresistors is very low. They are capable of responding well to light flashes which last less than one millionth of a second.

Like in ordinary photocells, the number of harmful thermoelectrons in photoresistors increases on heating. Therefore, photoresistors have to be cooled. But in this case the need to cool becomes the more urgent, the longer the wave the photoresistor is expected to respond to. Thus, if we wish the device to react to a wave-length of 10 microns, we must cool the photoresistor, optics and all the rest of the unit to a temperature much below plus 15 degrees. Otherwise, all the parts of the unit will also radiate energy at approximately the same wave-length and thus give rise to a parasitic radiation which will completely mask the wanted signals. We know that thermal energy always passes from a warmer body to a cooler one. Infrared rays are heat rays which carry thermal energy over distances. Hence, if the photoresistor has a temperature higher than or equal to that of the radiating body, it will not be able to pick up such a radiation. The new types of photoresistors are cooled to minus 200 degrees and lower.

It has been said that the sensitivity of photoresistors is very high. But in the visible light range it is much inferior to that of the eye. Nevertheless, in many cases photoresis-

tors successfully replace the human eye. The armies of many countries are equipped with homing-type missiles, that is, rockets which, on "seeing" the target, reach and destroy it without receiving any control commands from without. Such rockets often employ optical homing equipment where the role of the eye indicating the direction of the target is played by a photoresistor, and that of the brain—by a special electronic circuit to which the photoresistor signals are fed.

But military engineering is not the only field in which homing missiles can be used. Recently an American magazine made public a plan in which automatic rockets are employed for forest fire control. This plan is based on the ability of photoresistors to respond to infrared rays which are radiated in great quantities by any body heated to the ignition point. Such automatic homing missiles will be installed on towers built in forested areas. When a fire appears the missiles in whose field of view it happens to be, start off automatically and, on reaching the fire, explode, throwing out a large quantity of fire-extinguishing chemicals.

If we take into account that some types of photoresistors respond to the light of a cigarette up to 800 metres away, we can well imagine that such rockets must be very good firemen. And we doubt whether anyone would care to smoke in a forest which is under the care of such vigilant guards.

A Light Amplifier

The photo-emissive effect forms the basis not only for photocells and photomultipliers, but for image converters as well. Now we know that taking advantage of the photoconductive effect, scientists have built devices that differ little from the photocell and the photomultiplier. But is it not possible to make a device similar to the image converter, based on the photoconductive effect?

It was only a few years ago that scientists were first able to give a positive answer to this question, when they created the so-called light amplifier. Sometimes, to emphasize the difference between this instrument and the image converter, which is also a light amplifier, the new device is

called a solid-state light amplifier, a semi-conducting light amplifier or even a light-amplifying picture panel, if the size of the screen is large enough.

The light amplification obtained in a solid-state amplifier, using cadmium sulphide as the material for the light-sensitive surface, may be as high as five hundred-fold, and still higher, if cascade circuits are employed.

As the principal element in solid-state amplifiers is the light-sensitive surface, which is made of the same materials as in photoresistors, it might be assumed that the advantages and shortcomings of solid-state light amplifiers are similar to those of photoresistors. And this assumption happens to be true.

Solid-state amplifiers are simpler in operation, more rugged and do not require unduly high voltages. They make it possible to obtain an image in a broader range of light waves. Some types of converters are very sensitive to x-rays. The use of light-amplifying picture panels in roentgenoscopy will greatly reduce the harmful irradiation of the patient and the physician. At the same time examination is made easier because the image is much brighter than on the screens used at present in x-ray equipment. Other types of solid-state amplifiers are sensitive to infrared rays, the wave-lengths of which are beyond the sensitivity threshold of image converters.

One of the major shortcomings of photoresistors is their inertia. It is especially felt in modern solid-state amplifiers. It manifests itself in the same way as the inertia of the eye—as after images (positive and negative, depending on the conditions). In life, after images rarely cause any trouble, and we hardly notice them. But in solid-state amplifiers after images are immeasurably more pronounced. They are sometimes very bright and persist for a fairly long time: the object may have disappeared altogether, but the image will still be visible as before on the screen of the solid-state amplifier. For this reason solid-state amplifiers are employed today only for observing invariable or very slowly varying images. It is to be hoped that in time this shortcoming of semi-conducting light amplifiers will be eliminated. But it remains to be seen whether they will then be able to retain their high sensitivity.

An Electricity Factory

Up till now we have been dealing with photocells which allow current to pass through them under the action of light only when a source of voltage—a battery, a rectifier, or the like—is connected to them. These photocells cannot put current into the external circuit of their own accord, no matter how intense the light illuminating them.

But it appears, there are photocells with other properties. Under the action of light they feed current to the external circuit in proportion to the incident light flux without the aid of outer sources of electricity. Photocells of this kind are themselves sources of electricity. They produce it from the rays of the incident light and are thus converters of light to electric energy.

Until recently such photocells were made exclusively of selenium. Amateur photographers are well acquainted with them, because the photocells in photoelectric exposure meters are selenium ones. But they are poor energy converters, their efficiency is very low, and therefore they are unsuitable for obtaining comparatively large quantities of electrical energy.

In recent years scientists all over the world have been working hard to develop highly effective solar energy converters. Such converters are often called solar cells. New semi-conductor materials are used to make them. Major achievements in this respect were scored by Soviet scientists under the guidance of Academician A. Joffe. The efficiency of solar cells is already high enough for them to be used as sources of electricity for feeding various electrical and electronic devices on Earth satellites and interplanetary stations.

We shall not be able to go into the details of operation of such photocells here. The processes occurring in the semi-conductor crystal used to make the solar cell are very complicated, and even scientists came to understand them fully only just recently. To describe them we should first have to explain a large number of important concepts concerning the physics of semi-conductors. Essentially, the operation of solar cells amounts to the fact that scientists

and engineers have found ways of making the charge carriers, liberated by the action of light, move in one direction only instead of at random in all directions.

Secret of the Code

You all know very well how telegraphic messages are transmitted with the aid of the Morse code. Whether wire or wireless communications are being used, the operator converts the text of the message letter by letter into combinations of electrical signals of different duration. Their duration varies depending on the rate of sending. The faster the message is transmitted, the shorter the signals. But irrespective of this rate, the ratio of duration of the signals is always the same: the dash is a strictly definite number of times longer than the dot.

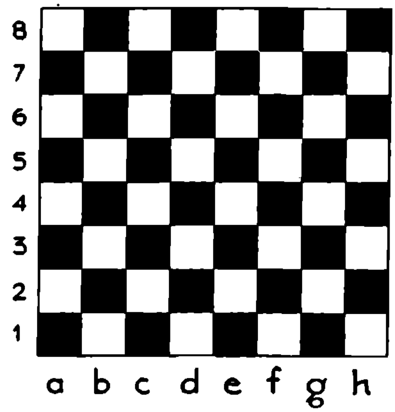
Using the Morse code, any message consisting of a text or of numbers can be sent. But not all messages, not all information can be expressed as a text or in number form. Many kinds of information cannot be adequately translated into words. Such, for instance, is the information contained in drawings, photographs and figures.

How is such information to be transmitted over long distances? Shall we have to content ourselves with the old way of sending them by post? Fortunately, inventors have found ways of sending images along wires or by radio by means of electrical signals.

But if textual or numerical messages could be converted into electrical signals by means of the vision, brain and hand of man, the conversion of images into electrical signals by these means is very tedious and cannot be employed in practice.

Still, it is worthwhile seeing how an image could be transmitted by methods of conventional telegraphy.

Suppose we have to transmit the image of a surface broken up into alternating black and white squares, just like a checker board. If we look attentively at the image of such a surface, we can easily think up the first, simplest way of transmitting it. It would be to inform the operator at the other end of the line by telegraph or wireless, using



Checker board.

the Morse code, that the image resembles a checker board and that it consists of absolutely white and absolutely black squares. After this we begin to send information about each of them. Those who play chess or checkers will readily understand the simplest way of doing this: a1-black, c3-black, e8-white, etc., until the information on all the 64 squares has been transmitted.

But this method of transmitting is disorderly and therefore involved and may lead to errors. There is no difficulty in simplifying the message considerably by sending the data on the colour of the squares in a definite order instead of at random—first, the data on the first row of squares (the first line) from left to right, then on the second row (second line), etc.

In this case the deciphered message would look something like this:

a1-black, b1-white, c1-black, d1-white, etc.
a2-white, b2-black, c2-white, d2-black, etc.
. . . .
. . . .
. . . .
a8-white, b8-black, c8-white, d8-black, etc.

You can see that when data are transmitted in such a way one and the same sign is repeated eight times in each line: this is the digit indicating the ordinal number of the line. To save time and cut out unnecessary characters containing no additional information, this digit should be transmitted only once. We factor the message, as it were, and place this digit at the beginning of the line. But this is far from all that can be done by way of simplifying. We can arrange once and for all with the receiving operator that we are not going to transmit the words "white" and "black" at all.

For short we shall send a dash (—) instead of the word "white" and no signal at all for the word "black", leaving a blank interval of the duration of one dash instead. Such absence of any signal is, essentially, also a signal of quite a definite meaning.

After fulfilling all these conditions our message will become much shorter without having lost any of its useful information, and will look like this:

1 a b—c d—e f—g h—
2 a—b c—d e—f g—h
....
....
....
8 a—b c—d e—f g—h

Thus, we have obtained a coded message which the operator will have no difficulty in deciphering, because we have given him the key to the code by preliminary arrangement. But this code is still rather complicated. There is much room for further simplification, if we remember that the order of transmission is strictly definite and unchangeable: first we send data on the colour of the squares in the first line from left to right, then of the squares in the second line, again from left to right, and so on.

Keeping this in mind, we need neither send the letter designations of the squares nor the line numbers, but use a special signal (say, the letter "p") to indicate the beginning of each line and another (say, "P") to indicate the beginning of the message. Then our message becomes still

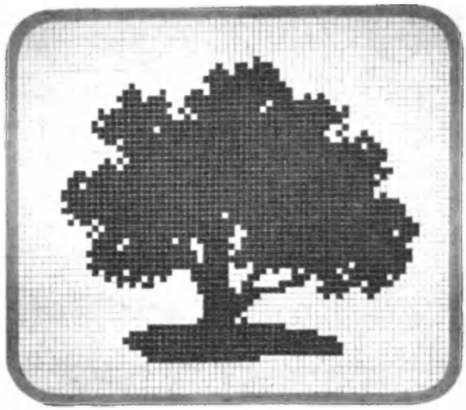
simpler without losing any of the information that interests us:

P p 0—0—0—0—
p—0—0—0—0
....
....
....
p—0—0—0—0

In this message zero stands for the absence of any signal, meaning a black square. Please note that with such a method of coding we can transmit data on any number of squares in each of the lines, and on any number of lines, without having to use digits or letters. If we had retained the letter designations of the squares we could not have transmitted data on more squares in each line than there are letters in the alphabet. But as it is, it would not matter even if there were a thousand squares in each line.

Thus, using a very simple code, we can transmit some of the simplest images, provided they consist of alternating black and white squares. However, many images (not to mention coloured ones) contain not only black and white, but various shades of grey as well. Sending such images is much more complicated. The transmitting operator has to assess the degree of blackness of each square and transmit his findings by means of a special sign. The human eye can distinguish 300 shades in the achromatic gamut. Therefore, 300 special signs would be needed. Actually, it is not necessary to transmit such a large quantity of shades. A very good image can be obtained by transmitting a much smaller number. In some cases it is permissible to divide the entire gamut of greys into eight gradations. Then only eight special signs are needed instead of 300. However, even in this case it is very difficult to send an image, the more so, that while the eye is able to distinguish such a large number of shades, it cannot determine the absolute degree of blackness by looking at only one spot. But even if the eye could do this either by itself or with the aid of some device, the transmission of even a very simple image would take far too long.

And, of course, nobody ever sends images by this method. The slow eye, hand and brain of man are unsuitable



The more squares the image is broken up into, the more details can be discerned.

for these purposes. But the photocell is excellently adapted for converting images into electrical signals. It faultlessly, and practically instantaneously, converts different degrees of blackness into currents of corresponding intensities.

As to the principle of coding and transmission, it remains the same, only the conventional signs are replaced by electrical signals of intensities proportional to the brilliance of each of the squares. The brighter the square, the higher the current and the stronger the signal. Besides these, there will also be signals indicating the beginning of the message and the beginning of each line of it.

Let us take a photocell and move it uniformly from left to right along the lines of our image. When it is over a white square the current will be the highest; above a black square the photocell will not conduct current at all. At the receiving end there must be another device which automatically converts electric signals into light of proportional brilliance. A gas-discharge lamp could be used for this purpose, particularly, a lamp filled with neon. A neon lamp burns the brighter, the higher the current flowing through it. Therefore, it will burn the brightest when the photocell is over a white square, and will go out altogether when it is over a black one.

By means of special devices the photocell at the transmitting end and the lamp at the receiving end can be made to move in strict unison and according to a pre-set order of data transmission: from left to right in each line and in the order of consecutive lines. Then, if we place the image under the photocell and a sheet of photographic paper under the neon lamp, we get differently exposed areas on the paper. Taken together, they make up the image. The smaller the squares into which the original image was broken up, or, in other words, the larger the number of squares we break the same image up into, the crisper the image we obtain. It is evident also that the more squares, the more time is required to transmit them unless special measures are taken. Such is the principle. But in practice the picture telegraph operates otherwise.

The image to be transmitted is pinned on a drum which rotates slowly and strictly uniformly during the transmission of the image. The image is focussed by means of lenses on to a photocell. The latter remains stationary, and instead of it, a very thin needlelike and very bright ray of light moves along the lines of the image at a strictly definite speed. This light ray is reflected by the surface of the image into the photocell. The reflected light will be intense if the point on which the incident light falls at the given moment is a light one, and will be faint if the point is dark. The strength of the current flowing through the photocell varies in accordance with the changes in the amount of reflected light as the ray runs over the surface of the image. The current is amplified by an electronic amplifier and is sent by wire to the receiving station.

The light ray moves strictly in the order we have indicated—along the image from left to right. When it comes to the edge of the image it returns very quickly (almost instantly) to the beginning of its path, and at this moment the signal of the start of a new line is sent. After returning to the beginning of its path the ray does not go back along the same line again. While the ray was traversing the previous line and returning to its initial position the drum with the image on it rotated so as to move the image up exactly the width of one line, equal to the height of the ray section, and the light ray runs along a new line.

At the receiving end there is also a drum. Like that at the transmitting end, it is in complete darkness. It is timed strictly with the first drum. A sheet of photographic paper is pinned on the receiving drum and a very fine pencil of light from a neon lamp is focussed on it. The movement of this pencil is also very accurately synchronized with the movement of the beam at the transmitting end. The difference is that the brightness of the light beam at the transmitting end is strictly invariable while at the receiving end the brightness of the pencil varies in accordance with the signals fed to the neon lamp.

Both light beams are very fine so that only very small areas of the images are illuminated at a time. That is why even very minute parts of the images can be singled out, transmitted and reproduced.

This is how the picture telegraph works, this wonderful device combining the achievements of electronics, photography, light source techniques, optics, precision instrumentation and, of course, communications.

Special note should be taken of an exceedingly important property of the picture telegraph, distinguishing it from all devices known to date, including the eye.

In the eye, the crisp image obtained in the central depression was broken up into separate elements ("squares") by means of 40-50 thousand cones and was transmitted to the brain *simultaneously* along as many "wires"—nerve fibres. The whole picture perceived by the eye is transmitted along a million such fibres connected to 137 million rods and cones. It is very much the same in photography—the image is recorded *simultaneously* by an immense number of emulsion grains.

Picture telegraphy differs in this respect. It has only one "cone"—its photocell and one wire (the return wire is the earth). Nevertheless, the image is transmitted, and it is not a bad one. Anyone who has had occasion to receive a picture telegram has a good idea of its quality.

The transmission of images with the aid of one photocell and over one wire was made possible by the method we used of coding or converting the image to signals. According to this method the entire image was broken up into separate lines, and the lines into separate minute points of

different brilliance: the elements of the image. *All the elements of the image were transmitted in a strict order, in strict sequence.* With such a method the surface of the image was converted to a new quality, as it were—to time. This is a very important conversion, as it enabled transmission of the image over a single wire and in a comparatively simple way.

The Electronic Eye

The conversion of which we have just been speaking has been known to scientists for a fairly long time. It is used not only in picture telegraphy, but also in television, the most modern type of communications. Television would have been impossible without such a conversion, just as the invention of the "heart" of television—the pick-up tube, the most perfect electron tube based on the photoeffect—would have been impossible without it.

In the picture telegraph the surface of the image was scanned by a needlelike light beam. A similar method is sometimes used in television transmission. Here it is called flying spot scanning. In contrast to the picture telegraph, in television the scanning beam is not reflected from the surface of the image, but most frequently passes through it. It is clear that only images applied to a transparent base, such as cinema films, transparencies, drawings on glass, can be transmitted in this way. For example, the stationary inserts often shown during intermissions in television broadcasts are drawings on glass.

The photographs of the back side of the Moon, invisible from the Earth, were transmitted to Earth by means of flying spot scanning.

But this method is unsuitable for transmitting three-dimensional scenes and especially for out-of-studio telecasts. Therefore, a different method is used as the main one in TV broadcasting. Of course, the principle of successive, element-by-element transmission remains the same. In the television method of transmission the image is always fully illuminated, but it is broken up into separate elements ("squares") by means of a large number of photocells. Their number is large enough to transmit all the elements of the

image. In the Soviet TV system the image (frame) is divided into 625 lines. Each line contains 865 elements.* Hence, the whole image is divided into $625 \times 865 = 540{,}625$ elements. At first glance it seems impossible to put together such a large number of photocells. True, this number is much smaller than the number of light-sensitive cells in the retina, but it is nevertheless very large. Inventors have found a way out of this difficulty: they suggested substituting this large number of photocells by a single cell, but one of a specific kind. This photocell is called a mosaic.

Mosaic.... Does not this word bring up associated ideas? You probably immediately thought of the retina of the eye, resembling a mosaic made up of rods and cones. And this is no accidental coincidence. The television mosaic is also made up of an immense number of separate light-sensitive grains each of which is a very tiny photocathode or a microscopic photocell.

Mosaics are made by placing a carefully treated and cleaned plate of transparent insulating material in a special apparatus, and applying to one of its surfaces minute drops of a light-sensitive substance, of the same kind as is used in the photocathodes of ordinary photoelectric cells. These drops are applied by means of a special atomizer. It is no easy thing to make a good-quality mosaic. All the minute grains have to cover the entire surface uniformly and at the same time they must not touch each other. If there is electrical contact between them the separate miniature photocathodes will merge into a single large cathode, with which it will be impossible to break the image up into separate elements.

The mosaic is set in a special electron tube—a pick-up tube. Like in conventional photographic cameras, the image is projected on to the mosaic surface by means of lenses. Under the action of light the photocathodes emit more or less electrons, which are attracted by a special collecting electrode. These electrons themselves are not needed. What

* Actually, for a number of reasons, the line is broken up into a smaller number of elements. The number of elements per line in low-quality TV cameras and receiving sets may be as low as 400 or 450.

is important is that in yielding electrons the light-sensitive grains of the mosaic become positively charged. The magnitude of the charge depends on the illumination of the grain, on the brilliance of the "point" of the image focussed on that part of the mosaic.

Now, is it necessary to have conductors leading from each of these photocells? A total of 540,625 wires? Of course, not! This is where the principle of converting the image into time comes in—the principle of consecutive element-by-element transmission of the image. Owing to this principle we can substitute the 540,625 separate conductors by a single one with a contact on its end that connects with each of the photocells in turn, according to the laws of the conversion.

How does this contact move? The law of its movement remains exactly the same as the law of movement of the scanning beam. The contact moves at a strictly constant speed from left to right along a horizontal row of mosaic grains, or line, as it is called. On arriving at the right-hand end of the line it returns instantaneously to the left-hand end and starting at the beginning of the next line, resumes its uniform motion. After scanning all the lines in this way the contact instantaneously returns to its initial point at the beginning of the first line. And this keeps repeating again and again, as long as the television programme lasts.

The contact would have to move at a very great speed. Thus, if the width of the mosaic is 12 centimetres and the scanning standard is 625 lines, the contact must run 150 metres in the time one frame is transmitted, that is, in 0.04 second (in Soviet television the accepted frame speed is 25 per second, which is quite sufficient, from the point of view of the inertness of the eye, to eliminate flickering and for all movements to be perceived as continuous), or 3,750 metres per second.

This is an immense speed. And no ordinary conductor, no ordinary contact could be made to move so quickly. Therefore, a conductor, a contact of a special kind is used—a very fine electron beam. There is no difficulty in making the end of an electron beam contacting the mosaic move at so high a speed.

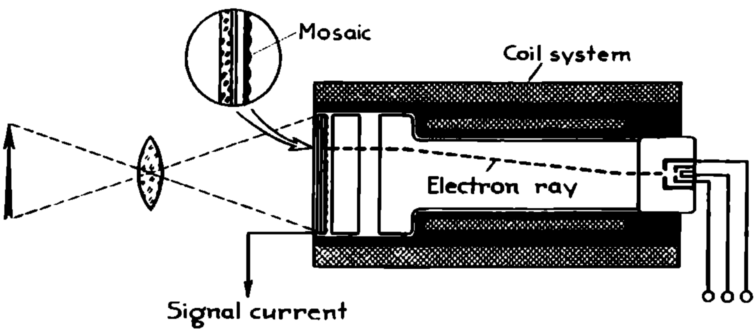


Diagram of an orthicon-type pick-up tube inserted in a system of electromagnetic coils.

To give a better idea of what has just been described, it will be best to examine the design of one of the types of pick-up tubes, known as the "orthicon".

As is evident from the drawing, the orthicon is an elongated glass cylindrical bulb widened in the front part. Inside the bulb is a mosaic and several electrodes. After the tube is made, as much of the air as possible is pumped out of it.

The mosaic is fixed to the inside of the front end of the tube. A thermocathode is installed at the other end. It is heated to a high temperature by means of a special electric heater which is, essentially, a wire wound into a miniature spring, resembling the element of an electric stove. The electrons emitted by the thermocathode fly in all directions. To shape them into a very narrow beam of electrons flying in one direction and to impart the necessary velocity to them, a special electron-optical system, consisting of the electrodes mentioned above, is placed inside the tube.

On the outside the tube is encircled by a long electromagnetic coil—a solenoid. Direct current is passed through the coil, and the resulting magnetic field makes it possible to draw the electron beam out very thin.* Two more pairs

* The section of the electron beam is made as round as possible. The diameter of the beam section at the point of its incidence on the mosaic must be exactly equal to the width of one line.

of coils known as the deflecting coils are placed between this coil and the bulb of the tube. Alternating current of a specific kind is passed through each of these pairs. Under the action of the two electromagnetic fields caused by the currents flowing through the two pairs of deflecting coils the beam is deflected in two directions at right angles to each other. The rate of vertical deflection of the beam is different from its rate of horizontal deflection.

The pair of coils deflecting the electron beam vertically makes it move slowly and uniformly downwards along the mosaic, and then return quickly to its initial position. The other pair of coils deflects the beam at a uniform rate horizontally from left to right, and then returns it instantaneously to the left edge.

The frequency of the current in the vertical deflection coils is much smaller than that of the current flowing through the horizontal deflection coils. That is why the vertical speed of the beam is much smaller than its horizontal speed. Consequently, the electron beam will draw as many horizontal lines (actually they slope slightly from left to right) as the number of times its line speed exceeds its vertical speed or frame repetition rate, as they say.

A similar method of consecutive scanning of the image, or resolving it into its elements by means of an electron-ray tube was suggested in Russia in 1907 by the inventor B. Rosing (1869-1933).

Thus, an electron beam incident on the mosaic plays the part of a conductor, a contact which successively closes the circuits of all the elementary photocells. Each of them accumulates a positive charge on emitting electrons under the action of light. This occurs in each of the mosaic grains and lasts as long as it takes the electron beam to return to the grain after once leaving it. The time the electron beam rests on any given grain is very small.* But this time is quite sufficient for the thermal electrons of the beam to completely replace the emitted photoelectrons and to

* If the frame is broken up into 540,625 elements and they are all transmitted in 1/25 second, the time the beam rests on one of the elements is only 0.000 000 08 second!

return the positive charge of the mosaic grain to its initial value, that is, to zero.

As soon as the beam leaves the elementary photocathode the latter again begins to emit photoelectrons. It yields the more of them per unit time, the brighter it is illuminated. Such an alternating process of yielding photoelectrons and replacing them with thermal electrons continues in each of the mosaic grains throughout the television programme.

As the illumination of each of the mosaic grains is different, the electron loss in each will also differ. Therefore, the amount of electrons received from the beam as it moves from one elementary photocathode to another will vary. And since the beam is moving continuously, so will this amount keep changing continuously. The result is a pulsating current which is nothing but the image signals coded in the same code as before.

These signals are amplified by means of electronic amplifiers. Additional signals are fed into the latter, indicating the start of the horizontal (line) movement of the beam, and others indicating the start of the vertical movement of the beam (the beginning of a frame). These signals are known as synchronizing signals, because they are needed to deflect the electron beam in the receiving tube in strict accordance, synchronously, with that of the pick-up tube.

The image and the synchronizing signals are transmitted by radio or over a special cable to the image receivers—the television sets.

The orthicon has been described in detail here only because the important principles of pick-up tubes are best explained by using it as an example. But the orthicon is neither the only, nor the best in its "fraternity". There are much better types of tubes at present.

The first tube used successfully in television was the so-called iconoscope. At present it has almost entirely gone out of use and has been replaced by the more perfect super-iconoscope. Tubes of this type are widely used for studio broadcasts even today. During the many years of its existence the super-iconoscope has been well mastered by industry. It gives images of high crispness and repro-

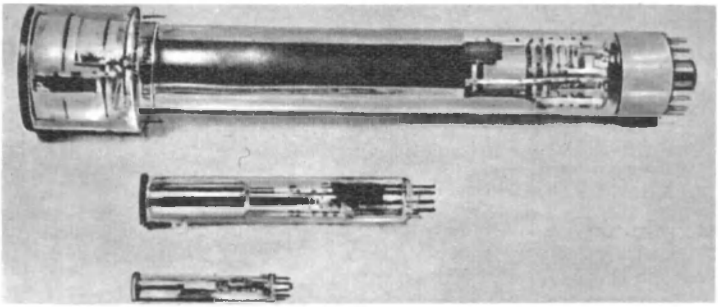
duces half-tones very well. But it has a major drawback—low sensitivity, so low that the scene transmitted has to be very strongly illuminated for normal operation of the telecamera. Such illumination can be effected in practice only in the TV studio with the aid of special lighting equipment. Another drawback of the super-iconoscope is that it is bulky, of complicated shape, and is therefore difficult to fit into the camera.

The orthicon, you already know of, differs little in sensitivity and image crispness from the super-iconoscope, and it is also used in television broadcasting. It is especially popular in Great Britain.

A new tube—the image orthicon—possessing very good parameters, appeared in the late forties. The most important of the parameters, its sensitivity, is so high that a good-quality image can be obtained in twilight or even in moonlight. The resolution of the image given by this tube is also very high: it can be brought even as high as 1,000 lines. The image orthicon has a good shape from the standpoint of design, but its overall dimensions are still large (about 500 or 600 millimetres long and maximum 50 to 60 millimetres in diameter). Besides, we must not forget the system of coils encircling the tube. It also takes up a lot of space and weighs a good dozen kilograms. Other drawbacks of the image orthicon are very complicated operation, high cost, short lifetime and low strength—it is very sensitive to strong shocks, concussions and vibrations.

Still, its advantages make up for all these serious disadvantages. The image orthicon is considered, and will be for a long time to come, one of the best tubes for use in cases where sensitivity is the prime requirement. Tubes of the image orthicon type are very widely used in TV broadcasting.

The image orthicon will soon be twenty years old, but it is still being continually improved. And just recently new major advances have been made in this respect. Not long ago there appeared new image orthicons whose sensitivity is so high that it surpasses that of the human eye manyfold. Our old friend, the image converter, helped to improve the image orthicon. It was employed to project an image of amplified brightness on to the image orthicon.



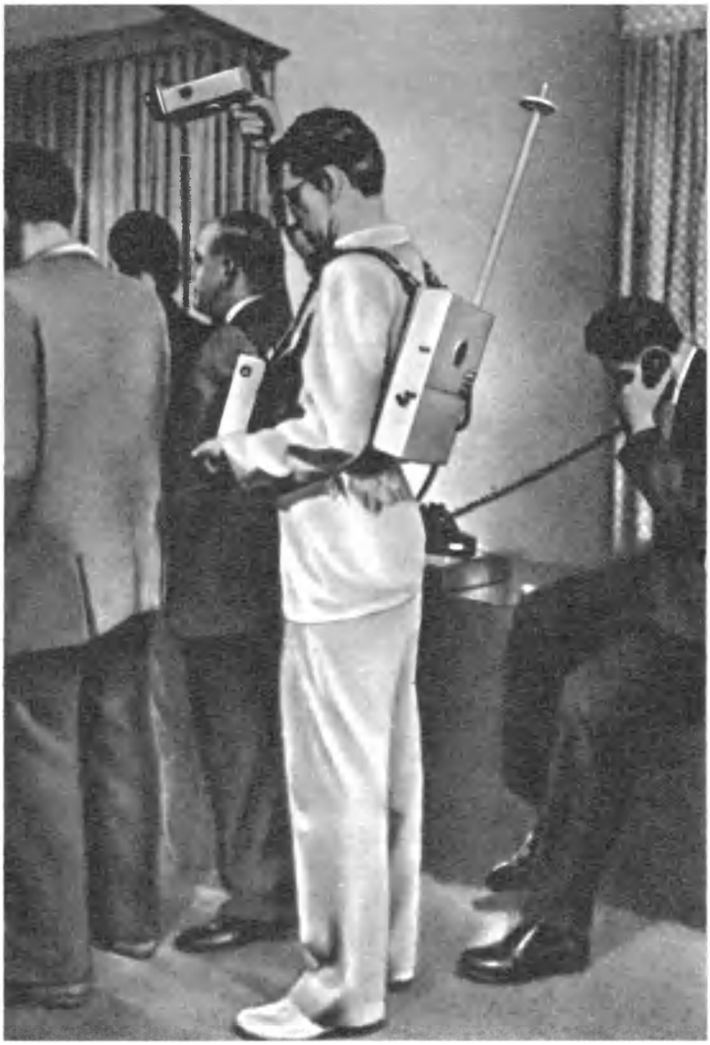
Television pick-up tubes: image orthicon, ordinary and miniature vidicons. Image orthicon is about 0.5 metre long; miniature vidicon is less than 10 centimetres long.

All the tubes mentioned up to this point were based on the phenomenon of emissive photoeffect. But we know that mastery of the conductive photoeffect has enabled engineers and scientists to make various devices having the same designation as devices based on the emissive photoeffect. Thus, it might be expected that pick-up tubes could also be made on the basis of the conductive photoeffect. And so they can.

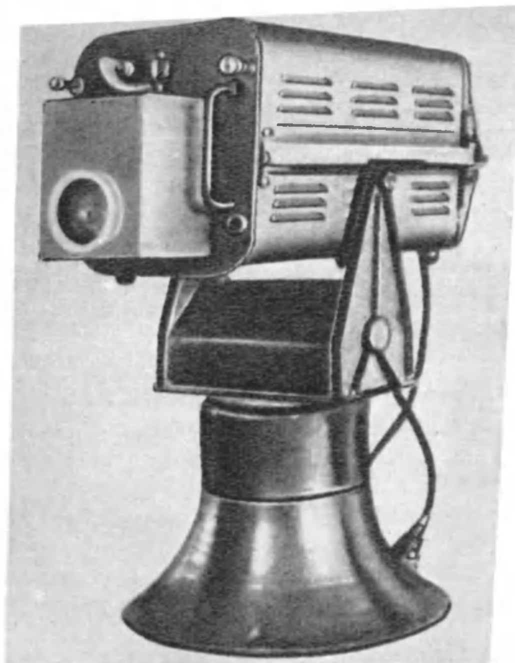
Such tubes have actually been developed. The first specimens appeared in the early fifties. Their properties are so good that at present they are not only the most widespread, but at the same time the favourite tubes of all television workers. Tubes of this type are called "vidicons".

The vidicon has many advantages. First of all, its sensitivity is very good. It is lower than that of the image orthicon, but much higher than that of all the other tubes, and quite high enough to give a good image in natural daylight (even in cloudy weather) and with ordinary room lighting. In image definition the latest modifications of vidicons are also not inferior to the image orthicon. In late 1960 it was reported that their resolution could be brought up to 1,000 lines.

It is also very important that the vidicon is exceedingly simple to operate, very reliable, shock- and vibration-proof, much more long-lived and cheaper. It has one more great



The reporter has a camera with a miniature vidicon in his right hand; in his left he holds a very small viewfinder by the screen of which he controls the quality of the image; the television transmitter is strapped on his back.



Transmitting camera of a special television unit with an image orthicon tube. The position of this camera and the setting of the objective diaphragm can be remote-controlled.

advantage—the vidicon is very small in size: its diameter is only 25 millimetres, and its length, 160. The weight of the coil system can be reduced to a few hundred grammes.

Nor is this the limit. Miniature vidicons (sometimes called minividicons) have already been made in a number of countries, not larger than a cigarette in size: 13 millimetres in diameter and 80 millimetres long, and their performance is excellent. The weight of the coil system may be not over 150 or 200 grammes. True, the highest image resolution obtained so far with its aid does not exceed 300 or 400 lines. But the minividicon is still a very "tender-aged" tube, and much is to be expected from it in the future. This is especially so, since owing to its very simple

design, the minividicon can be manufactured in automatic production lines in the same quantities and at the same cost as ordinary electron tubes. This will enable television to penetrate into many fields of human activity.

Like all devices based on the conductive photoeffect, vidicons can be made sensitive to infrared rays of lengths that no types of photo-emission tubes can ever perceive.

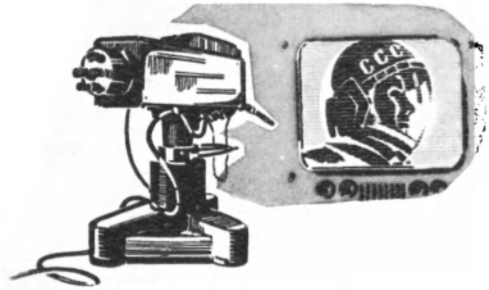
But this basis (the photoconductive effect) determines also the main disadvantage of present-day vidicons—their inertia. In this case the manifestation of this disadvantage consists in the blurring of quickly moving images and in loss of sensitivity when the tube is used to transmit such images. After images also appear, but in most cases they are almost imperceptible. Inertia is now combatted fairly successfully, and the inertia of the latest types of vidicons is already acceptable for telecasting.

Thus, you have read of the iconoscope and the super-iconoscope, of the orthicon and the image orthicon, and have apparently noticed that the tubes whose names begin with "super" or "image" are better than their predecessors. There arises the question: "Cannot a supervidicon or image vidicon be made?" Just now no definite answer can be given to this question. But that a tube of such a kind may appear is not impossible.

Just recently the working principle of a new tube was published, which might have been given such a name, though not quite deservedly. Bearing in mind that it still does not correspond 100 per cent to features one would expect to find in a supervidicon, the inventors called it "ebicon".

According to reports, the properties of the ebicon will be quite astounding. It is expected that the sensitivity of this tube will surpass the sensitivity of the eye and even the image converter, and will be close to the theoretical limit. The ebicon will make it possible to observe objects well even on a cloudy moonless night in autumn.

So far, this tube exists only on paper, but there is no doubt that in time such tubes will be manufactured, no matter how thorny the path to their practical incarnation.



TELEVISION

Television began to develop before World War II. The first television broadcast in the U.S.S.R. took place on April 29, 1931 in Moscow. The image was resolved into only 30 lines at a frame frequency of 25 per 2 seconds. This was an electromechanical television system. In it the image was scanned by a special revolving disk with spirally spaced apertures. This disk played the part of the scanning beam. Behind the disk was a photocell connected to an electronic amplifier. A similar disk was used to reproduce the image, but instead of a photocell a neon lamp with a large flat electrode was placed behind the disk.

Such television broadcasts were carried on for several years. In 1934 an exhibition was opened in Moscow, devoted to communications and radio. Among the latest novelties of radio engineering there were exhibited several red-brown veneer boxes with black bases and small windows. These were the first TV sets. Television broadcasts were also shown at that exhibition—hazy jerky pictures viewed through a lens no larger than a cigarette package. The sight delighted all viewers—most of them had never seen anything like it before. The images seemed a real wonder to them. And, come to think of it, they were a wonder.

A television image of low definition (broken up into only 30 lines).

A still greater wonder appeared in the next three or four years. During this relatively short time fundamentally new systems—high-definition electronic television systems—came into use. In them the image was transmitted by means of the tubes we already know about, and was reproduced on the screens of kinescopes.

Electronic television started in the U.S.S.R. in 1939. An experimental television centre was put in operation in Leningrad, which transmitted images with a resolution of 240 lines. At about the same time TV broadcasts were started in Moscow with a resolution of 343 lines. The frame frequency in Leningrad and in Moscow was the same—25 frames per second. At the same time the first televisors equipped with electron-beam receiving tubes—kinescopes—appeared on the market. The image size of these television sets was not large, about the same as in present-day portable televisors. But the set itself was very bulky, about the size of a small chest of drawers and was very expensive; it cost more than a motor car.

The third wonder in television appeared soon after the end of the war. During the war hardly anything was done

in the field of television—the attention of radio specialists was focussed entirely on the improvement of radio communications and radar. But with the return of peace, three years had hardly passed before television made an immense stride forward in all developed countries. Television sets became cheaper, and their output rose to hundreds of thousands and soon after to millions per year.

Image quality also improved greatly. In England resolution increased to 405 lines, in the U.S.A., to 525 lines. And in the U.S.S.R. image resolution rose to 625 lines. At present the standard resolution of 625 lines has been accepted all over Europe. Only in France was it raised recently to 819 lines.

The progress of television has not stopped at this. Scientists have set themselves a new aim—to make television coloured. The first system of high-quality colour television more or less suitable for widespread application was invented ten years after the end of the war. But it was very complicated, especially one of its main units—the colour kinescope.

A no less important problem on which specialists are working is beyond-the-horizon television broadcasting. It would be very convenient if TV programmes, like ordinary radio broadcasting programmes, could be received at long distances. Then ordinary radio receivers could be dispensed with and substituted by television sets.

Engineering has done a great deal in this respect. We already have a European TV network over which different countries can exchange television programmes. It was by means of this network that the inhabitants of many European countries were able on April 14, 1961 to see Spaceman I, Yury Gagarin, welcomed home and the demonstration that ensued at the Red Square. That was the first television programme relayed from Moscow over the European television network.

Long-distance television broadcasts are particularly important for the Soviet Union with its tremendous territory. An immense amount of work has been done, and now television programmes are regularly exchanged between many cities of the Soviet Union by means of radio relay communication lines.

Long-distance transmission of television programmes over radio relay lines is no longer the latest word in engineering. In the near future television programmes will be exchanged regularly, particularly between continents, mainly with the aid of special communication satellites.

The third task not quite completed as yet is raising the image resolution. In this respect television still lags far behind photography, cinematography and the eye. When the image is resolved into 625 lines the number of image elements is about 500 thousand. The image obtained in a microscope has about the same resolution. A high-quality photographic print made from a miniature negative may contain up to several million elements, these being photographic grains. If greatly magnified these grains will be perceptible to the eye when the print is viewed at a close range. At the distance of optimal vision equal to 25 or 30 centimetres the eye can perceive such graininess even when there are as many as 10 thousand grains per square centimetre. High-quality large-size photographs may contain several tens of millions of grains. Their definition is such that the eye is no longer able to discern the graininess of the image.

Fortunately, graininess of the image begins to cause unpleasant sensations only when the grains become too perceptible. And the standard resolution in telecasting is such that the definition of the TV image is quite acceptable.

But though it is sufficient for broadcasting, a resolution of 625 lines may prove, and actually is, intolerably low for a number of specific applications. There are at present special systems, designed for industrial and scientific purposes, which ensure much better definition: up to 1,000 or 1,200 lines (1,350 or 2,000 thousand elements). Unfortunately, this is the limit, which neither pick-up tube designers nor experts in the field of transmission and reception of radio signals have been able to exceed so far.

The problem of transmission of high-definition television images has not yet become one of primary importance, but it evidently will in the near future. And then science will solve it, of course. It is not improbable that the further knowledge we shall gain during this period on how the eye works will prove very useful for this purpose.

We have already spoken of the paths of development of engineering and of the chief stages of its progress. In our times electronics is one of the newest and most omnipotent branches of engineering. It has extended the possibilities of our senses to a hitherto unheard-of degree, having created most sensitive instruments for measuring temperatures, pressures, linear motion, velocities, mass, distances, radio, light, roentgen and nuclear radiations and a multitude of other artificial sense organs. Radioelectronics has considerably reinforced our eyesight, hearing and other senses.

Radioelectronics has conquered time and space. It has enabled men to hear and see over any terrestrial distances. And it has connected us with the first spacemen and automatic interplanetary stations.

We know about television broadcasting, about television for scientific purposes. It would be useful here to say a few words about another type of television which has begun to develop. In many countries special television channels have been reserved for transmitting various general educational programmes. Thus, television is becoming teacher to the millions.

In recent years, alongside TV broadcasting, major advances have been made in scientific and industrial television. Some day the history of television engineering will be written. And then anybody interested will be able to find out exactly who, when and for what reason was the first to use a television unit for scientific purposes. Maybe it was done to study processes involving radioactive radiations which are hazardous to the life and health of the workers; perhaps the first practical task fulfilled by television was to transmit a surgical operation for a large body of probationer doctors to see.

Be that as it may, the first attempts to transmit such television images did not require the invention of special devices—everything needed was already at the disposal of telecasting engineering. The first experiments confirmed the brilliant possibilities and prospects of applied television, and it came to be used more and more often, and soon became an entirely independent and exceedingly important field of TV engineering.

But it would not have made such fast progress nor gained such wide recognition if the television equipment for scientific and engineering purposes had remained the same as for conventional telecasting—cumbersome, difficult to operate and expensive. Specialists of all the industrially advanced countries have done a great deal to simplify applied television units and make them cheaper, reduce their size and weight, make them easier to operate and improve their reliability. Especially great progress was made in the improvement of pick-up tubes. Cameras have already been made in the U.S.A. and West Germany, using transistors and a minividicon, which weigh only 500 grammes. This is scores of times less than the weight of a conventional telecasting camera.

Of course, these achievements are due not only to improvements in electronic television circuits; a major factor was the invention of the vidicon—the best pick-up tube for applied television units.

This does not mean, however, that other types of pick-up tubes are not used in special-purpose telecameras. They are always employed wherever they are likely to be useful, especially when high sensitivity is required.

That is the reason why television units with image orthicons are employed in astronomy, and the tubes used in this field are not the ordinary kind, but special extra-sensitive image orthicons. There are such among them that have a sensitivity 100 times greater than that of the most sensitive photographic plates. But image orthicons are still considerably inferior to the latter in definition.

Any amateur photographer knows that you cannot make a good portrait if you illuminate the subject with direct hard light. Under such illumination the face looks flat and expressionless on the photograph. Front light obliterates the soft and gradual transitions of light and shade which make relief felt and bring out details. But the portrait will be no better if you use a strong bias light when photographing—in this case the shadows are too sharp. They darken part of the face and also conceal details. That is why portrait photographers most often use three lights: two bias lights and a diffuse one. This gives a portrait with good detail.

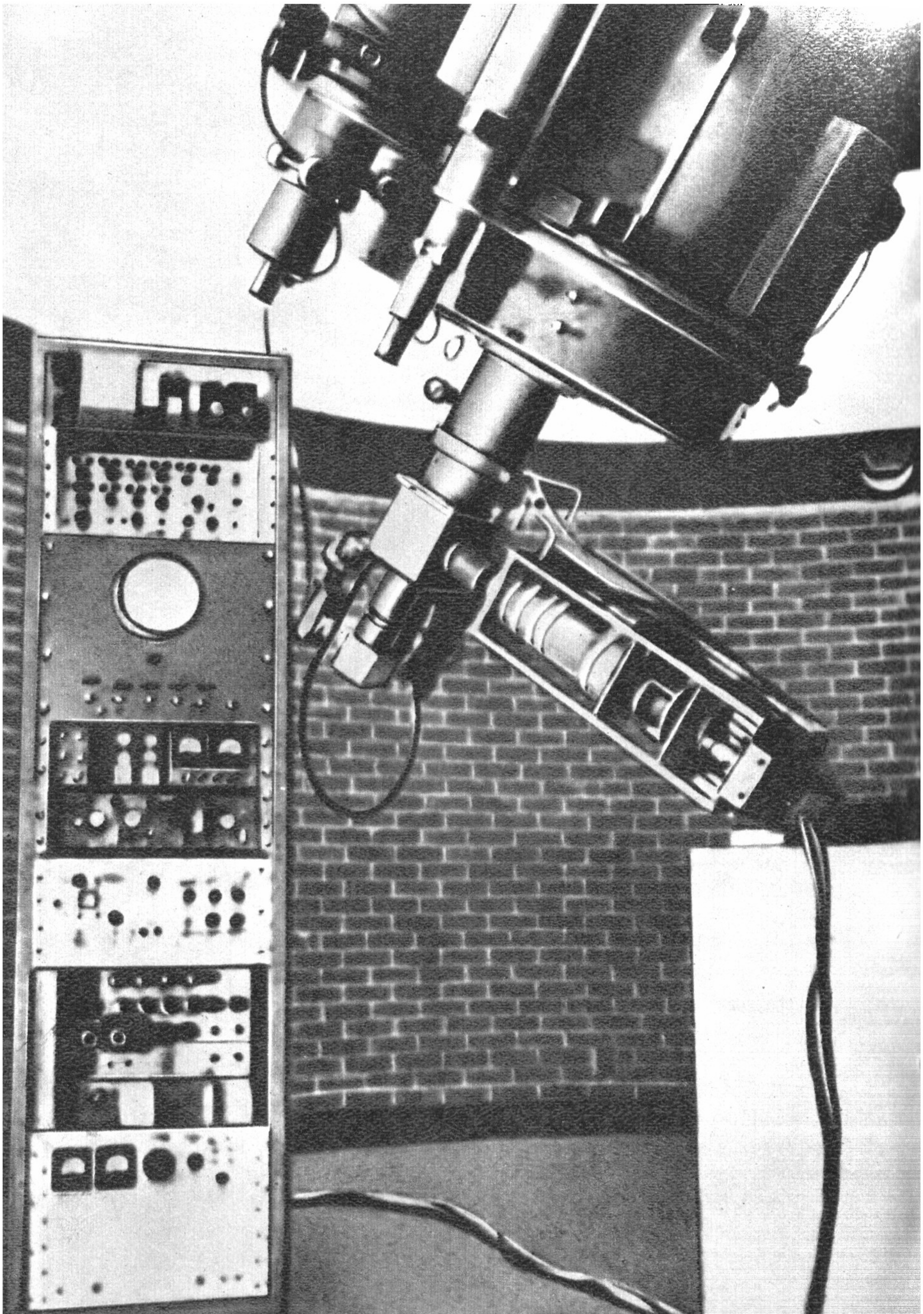
The Moon cannot be hauled into a studio and lighted up according to all the rules of the art. We are obliged to observe it illuminated by sharp solar light. At full moon the Sun's rays fall perpendicularly on the part of the lunar surface facing the Earth, and the rest of the time it is illuminated by a unilateral bias light. And since there is no atmosphere on the Moon, the shadows that fall on its surface are absolutely black and conceal all details in the shade.

Still, until recently, the best photographs were obtained when the Sun's rays did not fall perpendicularly on the part of the lunar surface facing the Earth. Under such conditions a fairly large number of details could be recorded, but certain other obstacles came up. They could be avoided at full moon, but then the photograph did not reproduce all the details of the lunar surface which could be seen by the eye through the telescope.

Not so long ago American engineers invented a special TV unit in which an extra-sensitive image orthicon was installed. They called it a "cat's eye". The very name shows that it is highly sensitive. And this is actually so: the television "cat's eye" can see much better than a real one. But its wonderful properties are not confined to high sensitivity.

Our eye is able to discriminate up to 300 gradations in the black-and-white gamut, and in this respect it is much superior to photography. But our eye is far inferior to the television "cat's eye". The latter responds to fantastically small differences in contrast, and, what is especially valuable, amplifies, increases them. For example, the "cat's eye" enables astronomers to observe the stars and planets in daytime. The image of these stars and planets on the kinescope screen was bright and contrasty.

The "cat's eye" helped astronomers to obtain a very good photograph of the lunar surface, made under perpendicular solar light, that is, at full moon. It increased the contrasts so much that the astronomers were able to record hardly perceptible transitions of light and shade and differences in colour. The photograph of the Moon obtained in this way was pieced together from 200 separate photographs. The diameter of the Moon in this picture is 1 metre.



Television attachment of a telescope. Front — camera and pick-up tube; back — receiver with screen on which image is observed.

The "cat's eye" proved very useful. But in working principle it does not differ in the main from conventional TV systems. In other words, it is a highly perfected organ of vision.

In many cases modern engineering strives to combine artificial sense organs with artificial thinking devices and actuating mechanisms. Such a combination gives birth to a new type of device—the automaton.

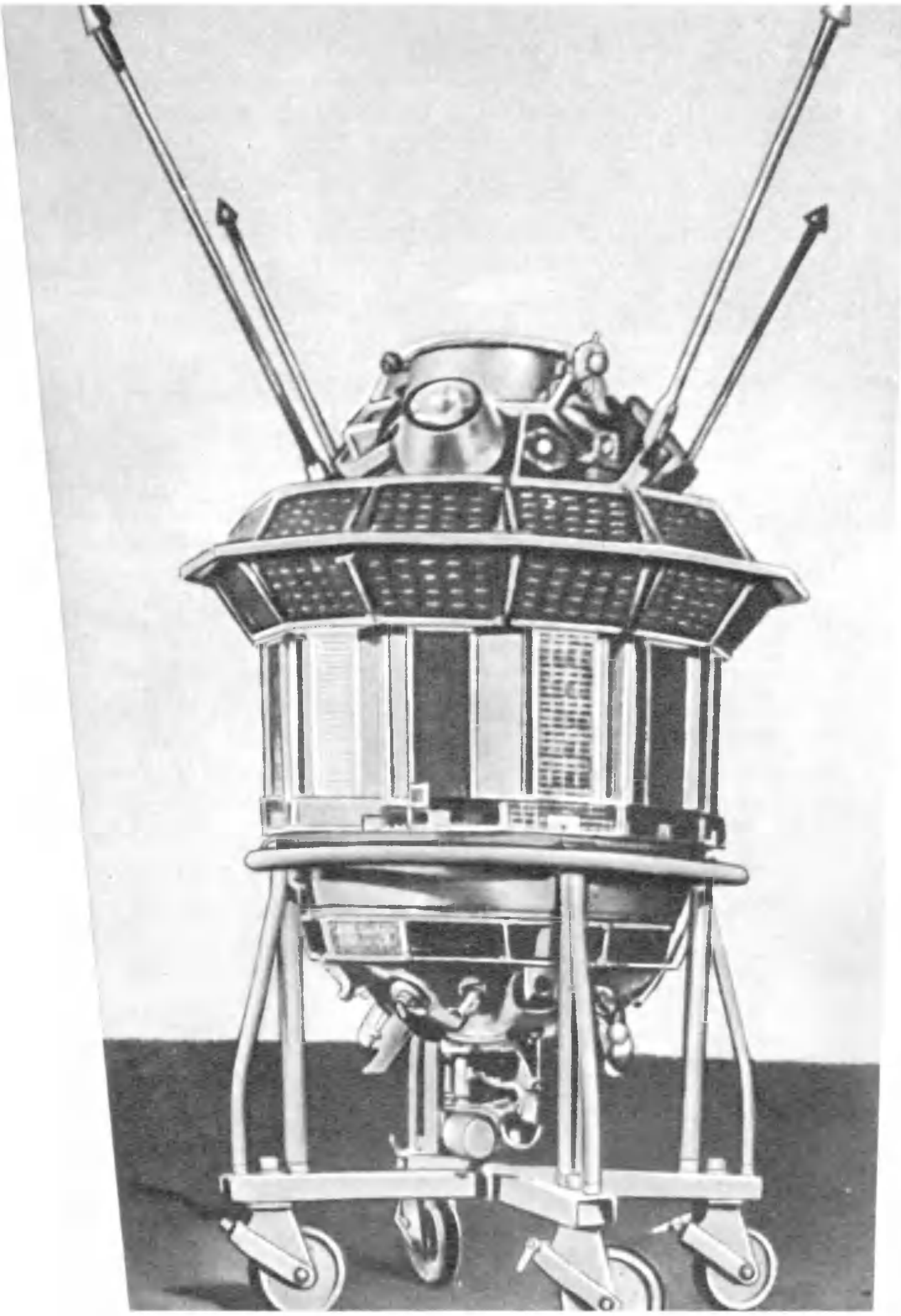
Engineers have built one of the types of television automatons for astronomical purposes. Like an ordinary TV unit it enables television images to be obtained and in this respect does not differ from other television systems. In combination with a telescope it enables observations of the luminaries to be made as with the "cat's eye". But an automaton can do more than that. The one we are talking about can independently keep the luminary continuously in focus.

Some of our readers may wonder what astronomy needs this for—the distance to the celestial objects is very great and practically does not change. But remember the hindering action of the changes in atmospheric density. They keep continuously and arbitrarily defocussing the image. Man is unable to follow this defocussing and correct it. But the automaton fulfils this task very well and in some cases makes it possible to decrease the harmful effect of atmospheric density changes.

Telecasting from Space

The first to visit the Moon and Venus were automatons. The automatic station Luna-9 soft-landed on the Moon and sent TV pictures of the lunar surface back to Earth. For the first time man was able to see the details of the relief of our eternal satellite. After a three-and-a-half months' flight through space the automatic station Venera-3 reached Venus and deposited the emblem of the Union of Soviet Socialist Republics on its surface. Throughout the flight regular radio communication was maintained with the station and a great deal of scientific information was received.

Evidently, automatons, rather than men will be the



Soviet automatic interplanetary station by means of which the back side of the Moon was surveyed.

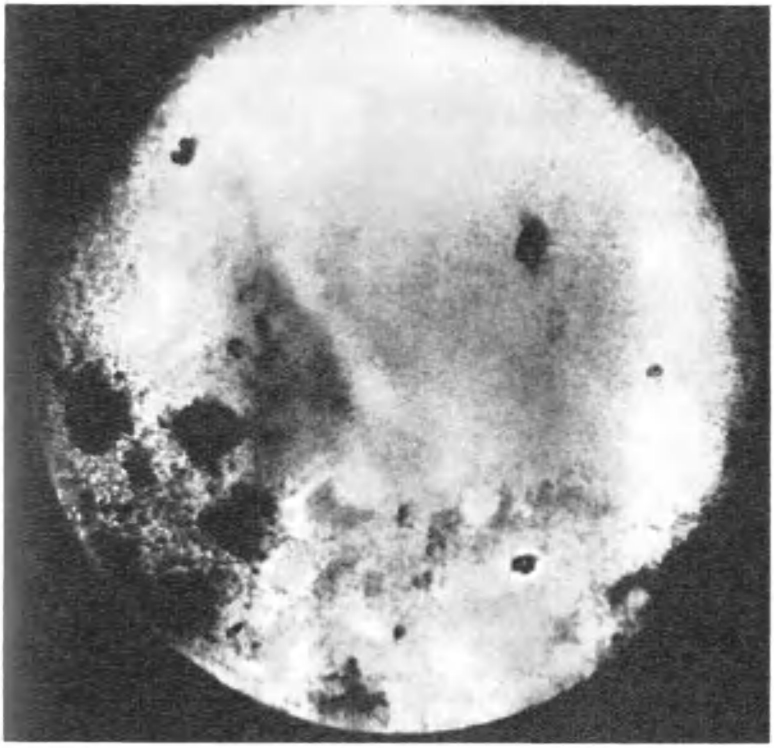


Image of the other side of the Moon transmitted to Earth by the automatic interplanetary station.

first to visit other planets as well. It will be a very complicated cybernetic machine consisting of many automatons designed for different purposes. And one of the most important among them will be an automatic TV unit with several telecameras and a television transmitter for sending the images to Earth.

As is known, there were no television devices on board the first man-made Earth satellites (neither on the Soviet, nor on the American one). Meanwhile, transmission of images from on board such satellites is of very great importance.

The absence of such devices from the very first satellites may be due to the fact that the first problems to be solved were those of launching the satellites and investigating the near-Earth space. But the subsequent launchings of satellites without television equipment can hardly be attributed to the same reason. Possibly, television technique was "unprepared" for such rapid progress in space research. Maybe it was that television experiments just did not happen to be included among the first-order problems of space research.

The first to make a space television unit were Soviet specialists. It was employed to transmit images of the invisible part of the lunar surface.

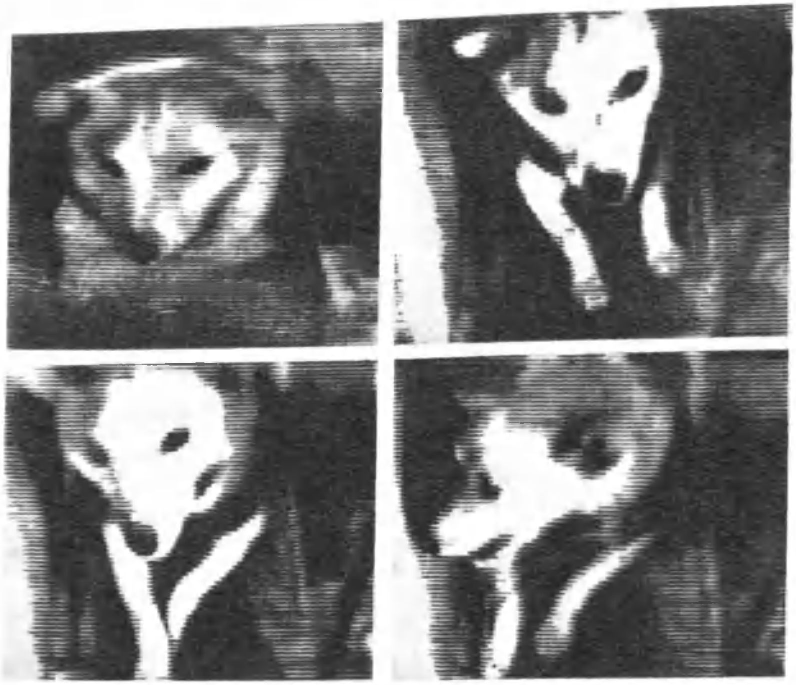
This unit had no pick-up tube. The Moon was photographed from on board the automatic station, then the film was developed and the photographic image was converted into electric signals by the scanning beam method. This beam was a bright point which moved over the screen of a miniature kinescope according to the law of conversion we already know. The brightness of the point remained unchanged. The light from it passed through the respective points of the photographic image and thence to the photocathode of a miniature photomultiplier. The amount of light arriving at the photomultiplier varied in proportion to the degree of transparency of the photographic image. The signals obtained on the last electrode of the photomultiplier were sufficiently intense to be radioed to Earth.

The quality of the images obtained was rather good. You can convince yourself of this by looking at the photograph transmitted by the automatic station, shown here.

On the basis of such photographs Soviet scientists were able to compile the world's first atlas of the back side of the Moon.

Television was also of great help to science during the flight of the spaceships with the first canine space passengers. Scientists were able to judge the behaviour of the animals and how they felt not only from the readings of their instruments, but could also see with their own eyes what was happening to them during the flight.

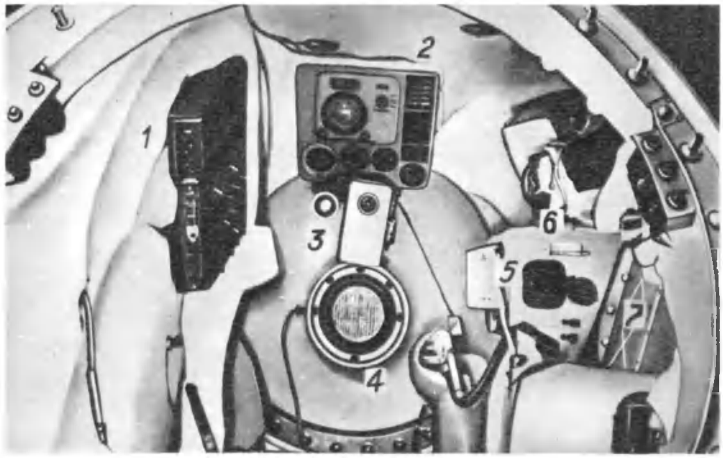
The spaceship "Vostok" had two television cameras installed in it. One of them transmitted full-face images



Television image of dogs transmitted from on board the Soviet spaceship satellite.

of the first spaceman, and the other, his profile. And during the flights of the "Vostok-3" and "Vostok-4" ships the images transmitted from the ships were relayed over the Intervision and Eurovision networks. Millions of people saw on their screens the smiling faces of A. Nikolayev and P. Popovich in the cabins of their ships.

U.S. experts made their satellite television units later than those of the Soviet Union. And it must be said that the first images they obtained from their man-made satellite were of very poor quality. It took an experienced eye to distinguish the cloud cover from the Earth's surface on them. In the following year or two they were able to improve their satellite TV units and recently they obtained quite good images of the cloud cover and the Earth's surface.



Interior of the cabin of the "Vostok" spaceship satellite: 1—pilot's control panel; 2—instrument board with globe; 3—telecamera; 4—porthole with optical device; 5—control; 6—radio set; 7—food containers.

The transmission of this kind of images is very important for meteorology. Man-made satellites enable the most detailed information to be obtained concerning the cloud cover over immense territories. Furthermore, this information is collected in a very short time, which is especially important for exact weather forecasts.

In the photograph reproduced here from a television image received from the "Tyros" satellite you can distinctly see the Red Sea, the Gulfs of Suez and Aqab, and the narrow dark ribbon of the Nile. This image was obtained at an altitude of 700 kilometres by means of a telecamera equipped with a wide-angle lens. The photograph covers a section of the Earth's surface about $1{,}300 \times 1{,}300$ square kilometres in area. The other photograph shows the mouth of the St. Lawrence River in Canada and the southern coast of the Labrador Peninsula. An interesting feature of the latter photograph is that the curvature of the Earth's surface can be seen on it distinctly.

Very recently, TV programmes began to be relayed successfully by means of satellites. For example, Soviet viewers were able to watch the television programme from

the U.S.A. on the day of President J. Kennedy's funeral; this programme was relayed to Europe by means of the "Telestar".

Space television is taking its first steps. Man has already succeeded in transmitting TV pictures directly from the surface of the Moon, and in getting shots of Mars. But if we compare the results obtained already with what should be obtained in the very near future, they may be considered rather modest. Television experts will probably have their hands full for quite a time before an effective system of transmitting detailed images from Mars or Venus is worked out. And not only the future of television depends on how well the experts cope with such most difficult tasks, but also that of many kinds of space investigations in general.

Television image of the Earth's surface transmitted from the U.S. satellite "Tyros". The Nile, the Gulfs of Suez and Aqab, the Red Sea and cloud cover above the Earth are visible.

This image was also transmitted from the "Tyros" satellite. In it you can discern the mouth of the Saint Lawrence River in Canada and the coast of the Labrador Peninsula.

New Trends in Old Fields

The resolving power and useful magnification of microscopes depend on the wave-length of the light rays in which the object is examined. The shorter the wave-length the higher the resolving power, and the more the magnification can be raised. That is why microscopes operating in ultraviolet rays are often employed. In them the image is either photographed or made visible by means of an image converter.

TV techniques can be of great help to microscopy. In speaking of microscopy we have so far paid little attention

to the optical properties of the objects under examination; yet, on them often depends the success of microbiological investigations. Many objects of biological origin are almost totally transparent and therefore cannot be examined by conventional methods. In order to study such invisible things they are dyed by means of special chemical compounds. In this way they can be detected and examined, but the trouble is that living microorganisms perish when they are dyed, while scientists are often interested in live rather than dead objects.

What can be done about this?

Recently developed television methods of observation have been a great help to microscope operators.

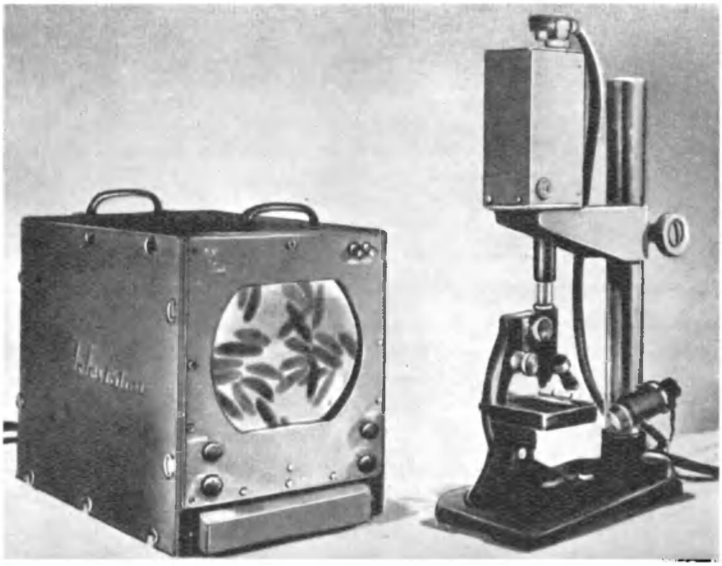
There are two kinds of television microscopes. In some the image is obtained by the scanning beam method. Others employ a pick-up tube, most frequently a vidicon.

Recall the "cat's eye" and its wonderful property of considerably enhancing contrasts. This is very useful in microscopy also, when studying objects of low contrast—the invisible objects mentioned above. The advantage of contrast-improving television microscopes is that when they are used the biological objects do not have to be dyed, and hence, they can be seen alive.

Television microscopy gives excellent results in ultraviolet rays. In this case the useful magnification can be as high as 2,000× and even 3,000×. Above we described the colour ultraviolet microscope. It often is very useful, but it is very labour consuming—three colour separation negatives have to be made, and besides, direct observation is impossible.

Television technique has eliminated these shortcomings and has made it possible to carry on direct observation of ultraviolet colour images on the screen of a colour television set. The first microscope of this kind was developed by a group of experts under the direction of our old acquaintance Land.

Though what we have just told about is a technical novelty, it does not go beyond the limits of conventional methods of microscopic investigations. Both the ultraviolet microscope and the study of invisible subjects, all this could have been accomplished, though less conveniently, without



Television microscope. Right—the microscope and telecamera; left—the videocontrol unit with bacteria visible on its screen.

the aid of television. Television offers new possibilities even in such an old sphere as microscopy. This is so because television enables the conversion of images into electrical signals. And the latter are the only "language" understood by electronic thinking devices and on the basis of which they can operate.

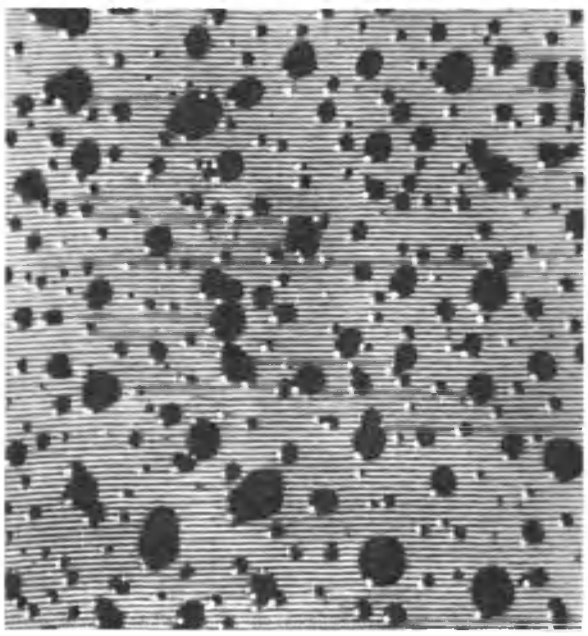
The first attempt to combine the microscope, television and a simple thinking device—an electronic counter—gave very good results. Such a complex instrument can count up quickly and accurately, without man's help, the number of particles or corpuscles in the field of view of the microscope. It can be used, for instance, to take a very rapid count of red blood corpuscles. When television automatons are constructed which possess shape vision they are sure to find wide application in microscopy, among other fields.*

* The first automatons of this kind, rather crude as yet, it is true, have already been constructed. These automatons are learning to read, and are already able to read printed texts.

Medicine, the oldest branch of human knowledge and human practice, was one of the first to make use of television.

The demonstration of surgical operations by TV makes it possible to train a large group of practitioners simultaneously. Without disturbing the surgeon by their presence, they can see all the stages of the operation even better than if they were at the operation table.

As to the television camera, it is installed in such a place from which observation is convenient, but where it is not in the operating surgeons' way. Lately telecameras are mounted more and more frequently right in the lighting fixture hanging over the operation table. There the camera



On this picture you see very clearly television raster lines and dark corpuscles with white points. These points are marks showing that the automaton has counted the particular corpuscle. In this way various microscopic particles can be counted, including red blood cells.

Transmission of a surgical operation by television.

is in nobody's way and at the same time occupies the best position for observation.

The first television transmissions of this kind were carried on with ordinary black-and-white units. But nowadays colour television has come into wide use for this purpose, giving a much better idea of the state of the organs operated upon and of the course of the operation.

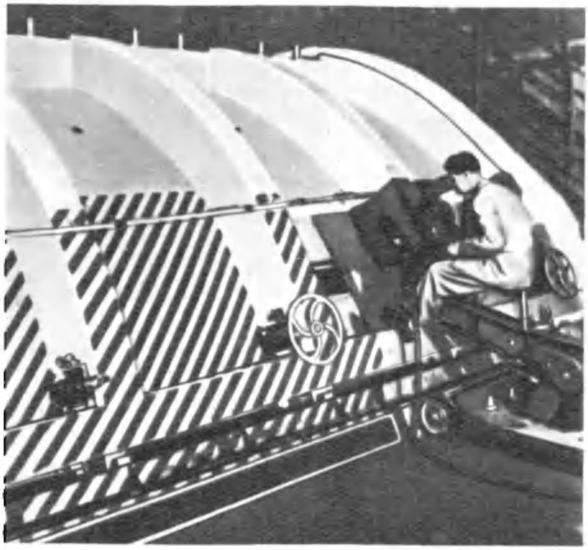
But television helps not only surgeons. It is no less useful in caring for patients. The telecamera has proved to be an excellent night nurse. In some hospitals cameras are installed in the wards, and with their aid one nurse can look after several patients in different wards simultaneously without disturbing them.

The Television Eye in the Air

Television is of very great help in testing and perfecting new types of aircraft and rockets.

You know what a big noise operating airplanes or rocket engines make. The noise is so great that without special means of protection men cannot stand it. They are not only in danger of growing deaf, but other vital organs may also be affected. Even many mechanical and especially electronic devices go out of order unless measures are taken to protect them. But noise is not the only hazard during tests of such engines. There are other reasons as well why these tests must be controlled and observed from a sufficiently large distance. That is why television units are now found at testing stands, and not infrequently colour units. Colour TV is very convenient for observing and studying the changes in colour of the flame and exhaust gases given off during the start-up of a powerful rocket. It was written in an American magazine that the telecamera is installed in a special sound-proof housing near the take-off site, and the signals from it are cabled to the control desk in a special concrete building . Here a colour TV set is installed, on the screen of which the image can be observed day or night without colour distortions.

Television is widely used during test flights of airplanes. In this case it is a great help both to the test flyer and to



Television camera used for viewing a wind tunnel.

the observers on the ground. Often several cameras are installed on the airplane instead of one. They are arranged in places that are inaccessible for direct observation both to the pilot and to those on the ground. The images are transmitted to the flyer's cabin and, if necessary, to the Earth.

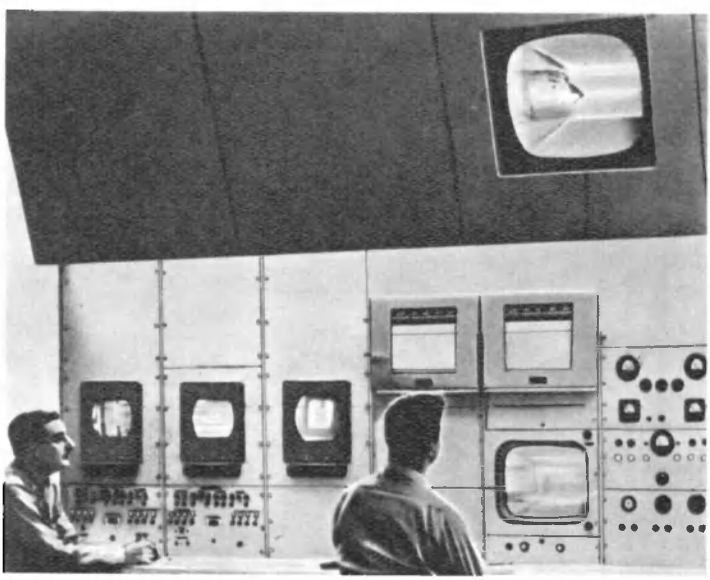
Thus, in England, television cameras which gave a good view of the airfoil considerably facilitated and speeded up the test of a new anti-icing system. A telecamera is often installed to send an image of the chassis to the pilot's cabin. This is a very convenient method of inspecting the operation of the key units of the airplane.

In our days there are usually several airplanes up in the air at a time, and their speeds are so high that despite the seeming boundlessness of the "third dimension" collisions do happen. All possible measures are taken to prevent them: for this purpose airplanes are equipped with radar, light signalling, apparatus for picking up the infrared

radiation of the heated parts of airplanes, a complex set of navigation and communication devices. Lately, attempts have been made to employ television for the same purposes. It will also help to reduce the probability of aircraft collisions.

As recently as the late forties and the early fifties future pilots could get their practical training only in flight. The trainee would go up together with his instructor in a special training airplane with twinned controls, and the trainee would learn to use his theoretical knowledge right there in the air. Such flights are still important, but nowadays they are preceded by a thorough training on the ground in conditions approaching actuality as closely as possible. It is carried out on special very complex devices known as trainers which are capable of simulating all kinds of flight conditions.

In the trainer the flyer is seated in a cabin which is an exact copy of the airplane cabin in which he will sub-



Control panel of a wind tunnel.

sequently fly. Everything, from the control stick or wheel to the last tumbler switch, is arranged exactly as in the plane and fulfils the same function as in the latter. The trainee is under the close observation of his instructor who is at the control desk of the trainer. The instructor can communicate with the trainee by radio, and can observe him by TV besides. Using special controls he can imitate any kind of conditions of flight, including emergency conditions. And the flyer is supposed to develop the ability to react quickly and correctly. After such a preliminary training the trainee finds it much easier to keep a real airplane under control.

Take-off and landing are considered especially responsible moments of piloting. That is why special take-off-landing trainers have been built in many countries. Television plays an important part in these trainers. In the cabin of the take-off-landing trainer the flyer has a TV screen before him. On it he sees the image of the air-strip, the buildings of the aerodrome and adjacent areas, various aerodrome services, planes on the flying field and special landmarks. This image shows everything exactly the same size as if the flyer were looking out of his cabin at the aerodrome while taking off or landing.

The plane "ascends", and all visible objects become smaller. The speed increases, and hangars, houses and signal lights run faster and faster across the kinescope screen. The plane takes a turn, and the image slopes and moves just the same as it would if the airplane were banking.

How is all this accomplished?

In principle it is simple. An exact model of the aerodrome and the adjacent areas is made and a mobile telecamera is installed above it. This is what transmits the image to the kinescope screen in the trainer cabin. When the flyer works his controls the camera moves over the model exactly as the plane would in response to the pilot's actions (whether correct or not).

That is the idea. As you see, it is quite simple and ingenious. But putting it into practice is a very complex job. The main difficulty is to make the mechanism for moving the camera. To be able to copy exactly all manoeu-

vres of the airplane this mechanism must be highly perfect and contain various cybernetic devices.

A great deal could be said about the use of television in aviation. But just now we shall confine ourselves to one more important example.

Television can be used instead of aerial photography. It will fulfil the same tasks as aerial photography, but besides, it will be able to send the image to the base immediately. The latter is especially important, for instance, when carrying on aircraft searches over ice-bound seas, burning forests, etc. But airborne television is still much inferior to aerial photography in a very important respect—in definition. So far the number of decipherable details on aerial photographs is many times larger than on TV pictures. Thus, in this case raising the definition of the TV image is one of the most important tasks.

The Control Room Engineer's Helpers

The transport dispatcher, the control room engineer at a large plant.... It is difficult to name a more important, more responsible and nerve-racking job. These men are first in command, obeyed to the letter by all enginemen and train formers, workers of sea and river ports and aerodromes, mine and factory transport. The engineer on duty in an electric power system occupies a similar post. One word, one movement on his part may direct the flow of millions of kilowatts of electric power.

If these engineers make a mistake, the consequences are not infrequently very grave. Such a mistake may result in great losses of money, and sometimes even of human lives. But the dispatcher or control room engineer can work efficiently and faultlessly only if he knows absolutely everything that is going on in all parts of the big complex enterprise under his charge. He becomes helpless like a general deprived of scouts and communications, if anything goes wrong with his communication and signalling system and the continuous flow of information is interrupted.

For that reason everything that may be useful, all the necessary means of communication and signalling are

Control desk of a control room television unit. Such a unit usually has many cameras installed at various points. The control-room engineer can view at will the image transmitted by any of the cameras. Besides, the engineer can remote-control the direction of viewing of any of the cameras.

placed at his disposal. In the control room you will find conventional telephones and a selector, and a control board—a large panel depicting the flow sheet of the section under control, on which various coloured lamps keep flashing on and off, indicating changes that are taking place.

Yet, today these means are not always sufficient. And more and more frequently the control room is equipped additionally with a TV set connected with telecameras installed at key points.

In the U.S.S.R. control room television was employed extensively for the first time in the field of metallurgy at the Magnitogorsk Iron and Steel Combine.

This is a tremendous enterprise. It includes not only blast-furnace, open-hearth plants and rolling mills, but mines and concentrators as well. They are spread over a very large area and are interconnected by railways continuously loaded with a traffic of ore, waste rock and slag trains running in all directions.

Dispatchers watch all the movements of the trains, see that they are put in on time. They must know everything that is going on on the railway, and for this purpose the dispatchers' posts were equipped with various kinds of communication and signalling equipment. And still mistakes occurred, trains not infrequently stood idle or were not fully loaded.

In 1958 the Combine began to install control-room television. With its aid the dispatchers could observe visually the movements of loaded and empty trains, and could see the ore unloaded into the bins of the concentrator crushing plants. They could see what was going on at the pit, could follow the operation of the mechanical shovels, watch the trains being loaded and moving from point to point.

Television is a major aid to the railways. A special type of railway TV unit, the "ЖТУ-3", has been constructed in the U.S.S.R. It is designed for observing the tracks and switching yards of large railway stations and helps the dispatcher to supervise all the marshalling operations at the station. The telecamera can be turned in any direction at the dispatcher's will. Besides, it is equipped with interchangeable lenses, their replacement being controlled by the dispatcher.

All this gives a very good view of what is going on on the tracks, and thus makes it possible to speed up train handling operations.

As in the case of the use of television for viewing big open spaces at the Magnitogorsk Combine, railway TV operates without limitations during the light part of the day, but at night it can work only if strong searchlights are available. Heavy rain, snow and fog also interrupt television operation. These drawbacks are the chief obstacle to the mass installment of TV units on all railways, waterways and airlines.

And nevertheless, many sea and river ports of the Soviet Union are already equipped with TV units. They help to watch crane operations and to keep an eye on the approaches and water area of the port even in bad weather.

Television and the Worker

Besides the control room, industrial TV is widely used in technology. Technological television differs from control-room television in that it takes direct part in the technological process, making the operator's job easier.

Here are some examples.

A unique double-cantilever concrete pouring crane was installed at the construction site of one of the world's largest hydropower stations, the Bratsk Hydro Project. The height to which loads can be lifted by this crane is 140 metres. The crane operator cannot see the point of delivery of the load well enough even in fair weather, to say nothing of conditions of poor visibility. In this case the natural and only possible solution was the use of TV. And it actually made it possible to control the crane successfully.

Ore, coal and rock are often loaded into cars by power shovels. It is not so easy even for an experienced operator to spot the bucket of a large shovel. That is why the bucket's contents do not always fall entirely into the car, and are sometimes partly spilled on to the tracks. In other cases, when the bucket is not spotted accurately it may crash against the side of the car and smash it. To avoid this the shovel operator has to be very careful and work slower.

Television has facilitated the shovel operator's job and helped him to increase his productivity. Here is one of the ways of controlling the operation of a power shovel by TV. The camera is installed on the shovel girder, and the receiver, in the operator's cage. This makes it possible to spot the bucket more accurately above the dump car. If two telecameras are installed, one showing the position of the bucket with respect to the middle of the car and the other relative positions of the bucket and car walls, all danger

of wall smashing and heaping the tracks with rock is eliminated.

Another convenient application of television is in the pouring of molten metal. The production of a high-quality uniform steel ingot depends on the conditions of teeming—the level of the poured metal must not be above the permissible and its surface must be clean.

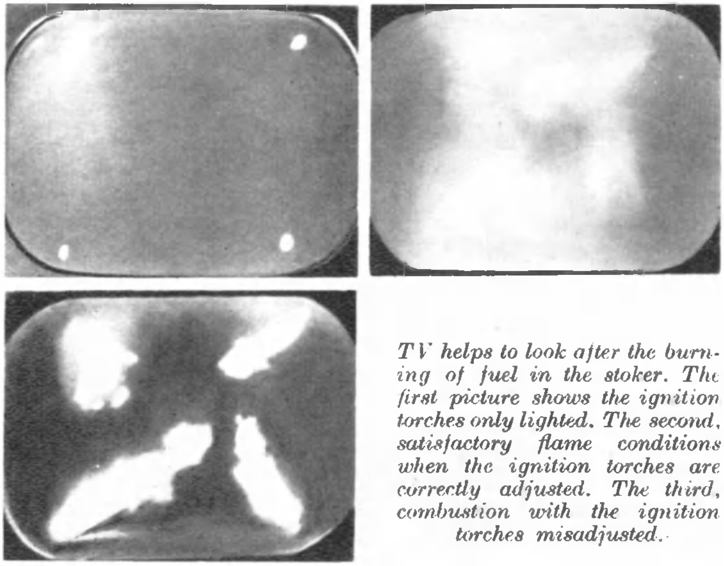
Before television inspection was introduced, teeming was controlled by a man who stood by the very mould. He made signs to the teeming crane operator. The latter was stationed at quite a distance from the mould and therefore could not see how the teeming was progressing. It is easy to see how toilsome and dangerous the work of the observer was. TV made it possible to relieve men from this job. The post of observer was taken by a telecamera which transmitted the image of the mould right to the control desk. To protect the camera from overheating it was placed in a special housing. Television has also facilitated the work of the operator, who instead of having to depend on the signs made by the observer, can watch the continuity of steel flow, the level of the poured metal and even the temperature by the meniscus of its surface, all by himself.

It is sometimes possible to look into a blast furnace or a boiler stoker at a thermal power station, but ordinary methods of observation do not give a correct idea of the process as a whole. For this purpose the combustion has to be observed in several parts of the furnace or stoker.

According to metallurgical experts it would be useful to employ industrial TV for inspecting the operation of blast furnaces, installing the pick-up cameras in the tuyere windows and sending the images to a receiving set installed in the foreman's room.

TV inspection of blast furnace operation is still in the experimental stage. TV fuel combustion control has already been put into practice at several power stations. This has proved very useful. Flame inspection enables the best conditions of fuel combustion to be maintained and saves hundreds of tons of fuel each month at every power station. Besides, it lowers the accident hazard.

The conditions of combustion at power stations are also controlled by indirect means—by the smoke coming out



TV helps to look after the burning of fuel in the stoker. The first picture shows the ignition torches only lighted. The second, satisfactory flame conditions when the ignition torches are correctly adjusted. The third, combustion with the ignition torches misadjusted.

of the chimney stacks. If the fuel is fed correctly combustion is more complete; therefore, there will be little smoke and it will be light in colour. Dark intense smoke is an indication of incomplete combustion. Transmission of a TV image of the smoke stacks of the power station to the control room operator or to the stoker foreman helps to improve stoker operation and, what is no less important, to lessen the contamination of the atmosphere in the vicinity of the power station.

Telemetry is the branch of engineering specifically concerned with the transmission of the results of measuring various values to distant stations. Very often (especially in electric power systems) the measured values are not transmitted directly, but are read off the primary meters.

Telemetry is a very young branch of engineering, hardly older than television. However, in the field of transmission of the readings of primary meters the specific means and methods of telemetry are being forced out by TV methods.

Until recently, primary meter readings were transmitted by wire or radio, and in electric power systems—over the

electric transmission lines by means of high-frequency techniques. This method of transmission had one important advantage over television—it was much simpler and did not require the laying of an expensive co-axial television cable. Attempts to transmit TV images over ordinary telephone, telegraph cables or electric transmission lines were unsuccessful until just recently. This important disadvantage of television systems was eliminated in the latest TV units, specially designed for these purposes. In them the images can be transmitted over any telephone channel. Owing to the principles underlying the design of these new television units, which use a vidicon as their pick-up tube, they have been made much more sensitive and they are especially good in cases where the transmitted image changes very slowly.

This is precisely the case with the transmission of meter readings: the meter indicator usually changes its position very slowly and smoothly, and more frequently its position remains practically invariable.

The resolution of the image in such systems is not inferior to that provided for by telecasting standards, that is, may be as high as 450 to 625 lines.

Trouble-free operation of a thermal power station depends on the reliability of operation not only of the electrical units of the station, but to a much greater extent, on the duty of the thermal units, especially the boiler. A very important characteristic is the water level in the boiler. Owing to the design of the boiler, water-level indicators can be installed only at a comparatively large distance from the station at which boiler operation is controlled (usually several storeys higher), so that a special worker called water-level inspector had to be employed to watch the water level. The water-level inspector's job, though not hard physically, is very tedious. It requires continuous concentrated attention and at the same time is unusually monotonous and uninteresting, and it is very difficult for a man to keep his attention concentrated under such conditions, no matter how hard he tries.

Attempts were made long ago to automate water-level inspection. The problem was solved by means of telemetric systems. But in recent years television came to be used for

this purpose. The worker controlling the operation of the boiler watches the water level by TV.

The invention of small-size telecameras gave television access to one more important branch of engineering. Small-size telecameras help to inspect various "bottlenecks"—pipes, drill holes and the like.

At present special TV units have been constructed in the U.S.S.R. and elsewhere for inspecting drill holes. The smallest hole diameter or narrowest space through which the camera can penetrate is 60 to 90 millimetres. And the depth to which it can be sunk may be several hundred metres. TV units make it possible to inspect the inside surface of pipes and holes as well as to determine the kinds of layers being passed in drilling and to watch the operation of the bit or drill.

Into the Depths of Seas and Oceans

TV has not only been up in interplanetary space, not only goes up into the air and down into the bowels of the earth. Very often nowadays it descends under water as well.

It is difficult to say when and for what purpose the first telecamera was let down into the submarine depths. It can only be asserted that this happened not earlier than the early fifties. But very soon after submarine television (this was published in British magazines) gave its first useful results as a participant in the dramatic search for the sunken British submarine Affray. Only thanks to submarine television was it possible to organize a rapid and effective search.

Just recently all information about the underwater world was obtained solely from the diver. This excluded the possibility of lengthy observations, because the time a man can stay under water is limited; it was also impossible to carry on observations at great depths or in stormy weather. As to the data obtained from the diver, they are much inferior in accuracy, detail and vividness to personal impressions, and may prove insufficient for making decisions.

Submarine television is free from all these shortcomings. It is a very great help in underwater construction work,

The sunken British submarine "Affray" was found by means of an underwater television unit. You can read the name of the sunken ship in the picture.

in inspecting the underwater parts of various structures in ports, in the construction of dams, and besides, it saves time and money.

Several first-class submarine TV units have been constructed in the Soviet Union. One of them was awarded the "Grand Prix" at the Brussels World Exhibition.

Two basic difficulties are encountered in designing submarine TV cameras. One of them is that the direction of view, the direction in which the optical axis of the submarine camera lens is pointed can be stabilized in space only by means of very complicated contrivances. It is still more difficult to control this direction remotely.

Suppose you let the camera down under the water on an ordinary wire rope. Nothing can keep it from rotating about its vertical axis even if the torque is very small. Such stresses always arise under the action of submarine streams or the residual stresses in the rope. Hence, the

designers of submarine telecameras were required to solve questions concerned not only with the transmission of the image and the construction of a water-proof housing, but in equal measure, with the construction of adequate remote control apparatus which would enable the direction of view to be set as desired.

One of the methods suggested was to control the camera with propellers. But this method has two important drawbacks: in the near-bottom region such propellers would raise the slime and mud from the bottom and make the water muddy; besides, the operating propellers would frighten away the underwater fauna.

Another method is based on the use of gyroscopes—special devices possessing the property of maintaining an invariable position in space. Devices by means of which it is possible to stabilize direction in space with the aid of gyroscopes are called inertial platforms. The use of an inertial platform with the transmitting camera arranged on it is, in principle, a solution to the problem, however, the design of the submarine camera is very complicated and expensive.

Yet, neither of these methods is sufficiently simple or sufficiently good. Therefore, the camera is very often made without any remote control contrivances, and it is operated by a diver. In most cases even such application of submarine television is quite justified and very useful.

The second difficulty of submarine television is of a fundamental nature. It relates to the optical properties of water. Water is much less transparent than air. The distances over which objects can be distinctly discriminated are a matter of metres, and that only provided the water is perfectly clear and calm and the illumination is bright enough. The distance of visibility is especially small in river water.

One of the methods of increasing the distance of visibility is to use contrast enhancing devices of the kind employed in the "cat's eye".

A second method is to use longer light waves. True, in this case it is still a question whether the gain will be very great.

The third method is especially interesting. The propaga-

tion of sound is also a wave process. If a sufficiently high frequency of vibration is selected—in the ultrasonic range, diffraction will be perceptible only when passing small obstacles, because the length of the ultrasonic waves will be very small. Such ultrasonic waves have much in common with light waves in the sense that certain optical laws are applicable to them. It appears that these waves can be focussed with the aid of special devices like light is focussed by lenses. These devices are therefore called acoustic lenses.

Now, if we "illuminate" space with an ultrasonic projector, the reflected supersonic vibrations can be focussed by means of such acoustic lenses in a certain plane. The result is an ultrasonic "image". By using special ultrasonic receivers this "image" can be converted into electric signals in the same way as in TV. Then these signals are fed to an amplifier and thence to a kinescope. What we see on the screen is a real image. It is not so crisp as when light waves are used. But the distance of visibility is many times greater.

Ultrasonic television has already scored its first successes. The quality of the image is rather poor so far, but there is promise of better results in the near future.

The Eyes and Hands of the Experimenter

Physical and chemical experiments with radioactive materials are accompanied by harmful radiations. To keep the experimenter out of danger a number of complex protective measures are taken.

First, all the radioactive substances and all the apparatus needed for the experiment are placed in what is known as a hot cave the walls of which are impervious to the harmful radiations. The experimenter's post is outside the cave at a window glazed with a special brand of glass, also impervious to such radiations. Through his window he can observe the course of the experiment directly.

But how is he to carry it out, how to control it if he must not enter the cave?

Mechanics has provided the solution to this problem. It has created special mechanical devices called remote

An operator controlling a remote manipulator by means of a stereoscopic television unit.

manipulators which replace human hands. The experimenter controls the manipulators, and they do anything he wants them to, almost as well as his own hands. With their "fingers" they can pick up delicate chemical glassware, pour solutions, make weighings on a balance, etc.

Not infrequently the intensity of radiation is so high that direct observation of the experiment through the window becomes impossible. And this is where TV comes to the rescue. The telecamera replaces the scientist's eye.

You remember the simple experiment we made with two pen nibs or two matchsticks. That experiment demonstrated the great difference between monocular and binocular vision. Owing to this difference the use of a conventional "one-eyed" TV unit in the hot cave cannot ensure

adequate control with the remote manipulator, though it enables observation of the course of the experiment.

That is why the television units employed in such cases are made stereoscopic. They differ from conventional units in that the camera and the receiver are doubled. One camera and one receiver transmit and receive the image for the left eye, and the other camera and receiver, for the right eye.

But this is not all. In some cases colour data are also important. Then the stereoscopic TV unit is also made a colour unit.

AFTERWORD

And so, reader, we have come to the end of the book on the nine colours of the rainbow. And now at the finish-line I fell to meditating: what is it I have written about? The nine colours of the rainbow? The human eye? How people have been able to reinforce it with various clever contrivances?

Yes, a great deal has been written here about these things. But is this all I wanted to tell you? Of course, not. Another thing I wanted to tell about was how a whole field of science and engineering developed; about the obstacles and difficulties that stood and stand in its way; how people, fettered and restrained by the laws of nature, come to know these laws, and then taking advantage of them win freedom and power over nature. I wanted to show that no problem has arisen so far that human genius did not solve sooner or later. At the same time I strove to bring out the idea that the number of unsolved problems is not going to become smaller as science and engineering progress, but will continue to grow.

Nor was this all I wanted to say. Science and engineering did not arise and develop of their own accord. They were born of man. They are man himself. For lack of space little was said about people in the book, but they are behind everything the book told about: workers, engineers and scientists. I would like the book to treat not only of the nine rainbow colours, not only of the laws of optics,

but of vocations as well. Of vocations which, perhaps, some of the readers of this book will make their own.

In this book I omitted such an important question as optical spectra. Nor is this the only question I omitted. Nothing, essentially, was said here about how light is born or about the mechanism of its radiation.

To my great regret, I had no chance to tell about these things. Meanwhile, it was precisely in the technique of light radiation that a veritable revolution took place in the latter months of 1961. Scientists and engineers succeeded in creating light sources that exceeded the Sun in brilliance by many million times! Just a few years ago most people would have thought anyone crazy, who dared to declare such a light source possible. But now these sources exist—they are called optical quantum generators or lasers.

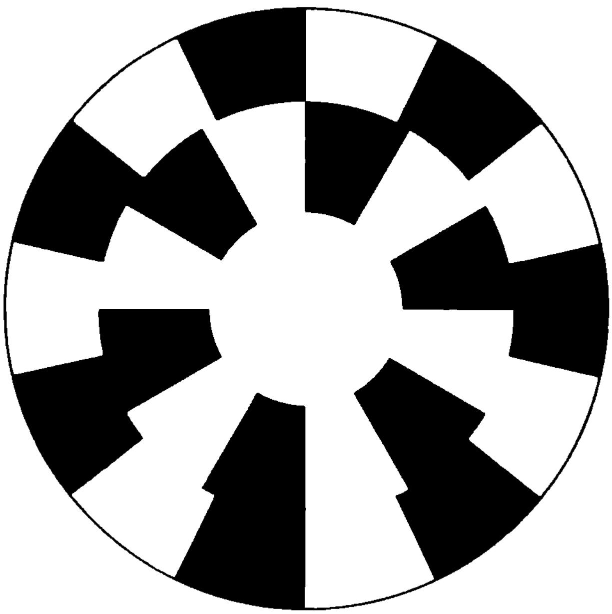
Lasers have already come into use for transmitting messages, TV signals, for direction and rangefinding, for surgical purposes (the intensity of the laser ray is so great that it acts like a knife), for machining materials and in many other branches of engineering. So far, these are but first attempts made mainly by way of experiment. But it is already quite clear that lasers have a great future. Lasers will be especially valuable as means of communication, remote control direction and rangefinding in space.

The very history of development of lasers is unusually instructive and interesting. The rate of their development is astonishingly high even for our times of unbelievably rapid progress of science and engineering.

It can be said without exaggerating that lasers are one of the greatest achievements of physics and engineering.

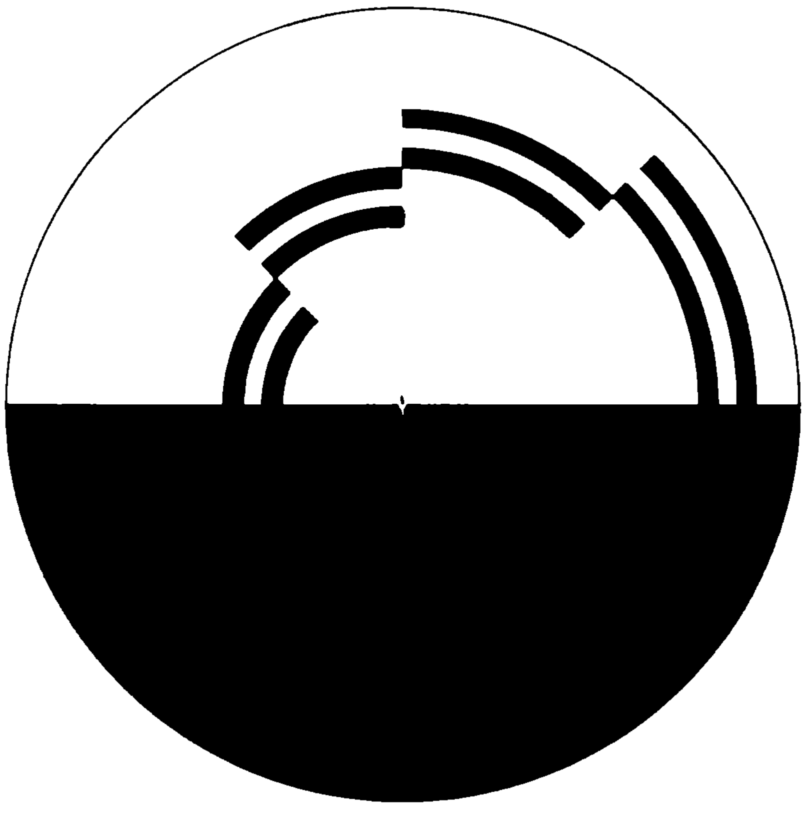
Lasers can be of immense use to humanity. But at the same time, they may do a lot of harm. At one time western publications seriously considered the possibility of employing the rays of lasers as "death rays". Fortunately, this proved unfeasible. Let us hope that in the near future mankind will do away with armaments altogether, and that all scientific achievements, all the efforts of man's genius will be employed only for the benefit and not for the annihilation of mankind.

APPENDIX I



Cut out the disk, paste it on cardboard and make a top of it. Try spinning it in daylight, in the light of an ordinary electric lamp and in the light of a fluorescent lamp.

APPENDIX II



Benham's disk. Cut it out, paste it on cardboard and make a top of it.

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The author, Alexander Steinhaus, is a Soviet specialist in electronics and TV. Many years of industrial experience served as a fertile ground for his literary career on which he embarked with ardour. He has written many sci-fic articles, some stories and a few books, among which are "The Nine Colours of the Rainbow", "A Factory Without Men", and others. At present A. Steinhaus is working at a large sci-fic book on television.